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Ph.D. Thesis

Design and Impact Assessment of Green Information Systems: the case of Energy and Carbon Management Systems in the Supply Chain

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Declaration

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Τις τελευταίες δεκαετίες οι επιχειρήσεις σε διάφορους κλάδους, υπό την πίεση των αυστηρότερων νομοθετικών απαιτήσεων, του αυξανόμενου ενεργειακού κόστους, των εντεινόμενων πιέσεων από συνεργάτες στην εφοδιαστική αλυσίδα για επίτευξη βιωσιμότητας καθώς και από την περιβαλλοντική ευαισθητοποίηση των καταναλωτών, εφαρμόζουν πληθώρα πρακτικών προκειμένου να αναπτύξουν περιβαλλοντικά πιο βιώσιμες εφοδιαστικές αλυσίδες (Abbasi &Nilsson, 2012; Ashby et al., 2012; Sarkis et al., 2012; Srivastava, 2007). Σε αυτό το πλαίσιο, η μέτρηση και η διαχείριση των περιβαλλοντικών επιπτώσεων και ειδικότερα της κατανάλωσης ενέργειας και των εκπομπών διοξειδίου του άνθρακα (Energy and Carbon Management) στα διάφορα στάδια της εφοδιαστικής αλυσίδας έχει αναδειχθεί ως μείζον θέμα (Hervani et al., 2005; Lee, 2012; Seuring & Müller, 2008; Seuring & Gold, 2013; Veleva et al., 2003). Ωστόσο παρά τις προσπάθειες των επιχειρήσεων και τη συνεχή πρόοδο στον τομέα αυτό, τα οφέλη της διαχείρισης της ενεργειακής κατανάλωσης και των εκπομπών διοξειδίου του άνθρακα δεν έχουν ακόμη πλήρως αποκομισθεί. Η έλλειψη τυποποιημένων δεικτών περιβαλλοντικής απόδοσης, η έλλειψη συστημάτων που συγκεντρώνουν μη-παραδοσιακές πληροφορίες (όπως π.χ. ενεργειακή κατανάλωση) και η ενοποίηση διαφορετικού τύπων πληροφοριών έχουν αναγνωριστεί ως οι βασικές αιτίες για την περιορισμένη υλοποίηση της διαχείρισης ενεργειακής κατανάλωσης και εκπομπών διοξειδίου του άνθρακα (Hervani et al., 2005).

Επιπρόσθετα, τα περιβαλλοντικά δεδομένα είτε απουσιάζουν πλήρως ή είναι απλώς διαθέσιμα συγκεντρωτικά (Bjorklund et al., 2012; Melville & Whisnant, 2014; Veleva et al., 2003), εμποδίζοντας έτσι τις επιχειρήσεις να αξιολογήσουν με ακρίβεια τόσο την εσωτερική όσο και την εξωτερική περιβαλλοντική απόδοση. Ενώ ακόμη και όταν τα οικονομικά και τα δεδομένα λειτουργιών είναι διαθέσιμα, διάφορα θέματα που αφορούν στην ενοποίηση των υπαρχόντων συστημάτων εξακολουθούν να χρήζουν αντιμετώπισης (El-Gayar & Fritz, 2006; Lee, 2003). Επιπλέον, στην εφοδιαστική αλυσίδα ο συγχρονισμός των διαφόρων εμπλεκόμενων (Hassini et al., 2012) και η αποτελεσματική συνεργασία και ανταλλαγή πληροφοριών μεταξύ αυτών πρέπει να αναπτυχθούν αποτελεσματικά προκειμένου να καταστεί δυνατή η από άκρη σε άκρη ροή των πληροφοριών (Banker et al., 2006). Τα παραπάνω καταδεικνύουν ότι η υποστήριξη της διαχείρισης της ενεργειακής κατανάλωσης και του διοξειδίου του άνθρακα στην εφοδιαστική αλυσίδα είναι μια απαιτητική διαδικασία και τα πληροφοριακά συστήματα μπορούν να λειτουργήσουν ως εργαλείο που θα υποστηρίξει την υλοποίηση της σε όλη την εφοδιαστική αλυσίδα (Dao et al., 2011; Melville, 2010).

Λαμβάνοντας υπόψη αυτή τη δυνατότητα, μια νέα κατηγορία πληροφοριακών συστημάτων ανακύπτει, τα Συστήματα Διαχείρισης Ενεργειακής Κατανάλωσης και Εκπομπών Διοξειδίου του Άνθρακα (Energy and Carbon Management Systems) (Melville & Whisnant, 2014). Τα Συστήματα Διαχείρισης Ενεργειακής Κατανάλωσης και Εκπομπών Διοξειδίου του Άνθρακα (ECMS) είναι ένας τύπος επιχειρησιακού πληροφοριακού συστήματος που «λαμβάνει ως εισόδους διαφόρους τύπους περιβαλλοντικών δεδομένων (π.χ. κατανάλωση ηλεκτρικής ενέργειας και καυσίμων, συντελεστές εκπομπών, μετακίνηση εργαζομένων και αεροπορικά ταξίδια), επεξεργάζεται αυτά τα δεδομένα σε χρήσιμες πληροφορίες (π.χ. megajoules ενεργειακής κατανάλωσης, εκπομπές αερίων θερμοκηπίου), και παρέχει βελτιωμένη λειτουργικότητα (π.χ. αυτοματοποιημένη υποβολή εκθέσεων, διαχειριστικούς πίνακες, αναλύσεις εφοδιαστικής αλυσίδας και διαχείριση ροής εργασιών)" (Melville & Whisnant, 2014).

Πιο συγκεκριμένα, τα συστήματα αυτά θα πρέπει να ανακτούν και να αποθηκεύουν πληροφορίες που σχετίζονται με την ενεργειακή κατανάλωση και τις εκπομπές διοξειδίου του άνθρακα από υποδομές μέτρησης της ενεργειακής κατανάλωσης, να ενσωματώνουν και να διαλειτουργούν με τα υφιστάμενα εταιρικά συστήματα (π.χ. ERP), να ερμηνεύουν και να ενοποιούν τα δεδομένα που λαμβάνονται από διάφορες πηγές και να ανταλλάσσουν δεδομένα με τα επιχειρησιακά συστήματα των εταίρων στην εφοδιαστική αλυσίδα. Αυτό το είδος των πληροφοριακών συστημάτων υιοθετείται με ταχείς ρυθμούς από τις επιχειρήσεις (Liu & Stallaert, 2010) και αντιπροσωπεύει μια αναπτυσσόμενη αγορά που προβλέπεται να ανέλθει στα 5,7 δις $ μέχρι το 2017 (Melville, 2012; Pike, 2011). Εκτός από τη διαχείριση της ενεργειακής κατανάλωσης και των εκπομπών του διοξειδίου του άνθρακα, τα συστήματα αυτά αναμένεται να επηρεάσουν την ανάπτυξη περιβαλλοντικά βιώσιμων εφοδιαστικών αλυσίδων υποστηρίζοντας την εφαρμογή περιβαλλοντικά βιώσιμων πρακτικών (Seidel et al., 2013) καθώς και την ενίσχυση της δυνατότητας λήψης αποφάσεων με βάση τις περιβαλλοντικές επιπτώσεις των εταιρειών (Butler, 2011; Vom Brocke & Seidel, 2012; Seidel et al., 2013; Shrouf & Miragliotta, 2015).

Παρά το αυξανόμενο ενδιαφέρον για τα συστήματα αυτού του τύπου, η εμπειρική γνώση για φαινόμενα που σχετίζονται με αυτά, όπως οι παράγοντες που σχετίζονται με την υιοθέτησή τους, οι αρχές σχεδίασής τους ή τα ζητήματα εφαρμογής τους (Melville, 2013), είναι περιορισμένη (Melville, 2012). Ο βασικός όγκος της υπάρχουσας έρευνας επικεντρώνεται στην ανάλυση των πληροφοριακών συστημάτων, ενώ περαιτέρω έρευνα θα πρέπει να διεξαχθεί για την ενδελεχή σχεδίαση, επίδειξη και αξιολόγηση αυτών (Malhotra et al., 2013, Melville, 2013; Seidel et al., 2013). Προηγούμενες μελέτες παρουσιάζουν γενικές αρχές σχεδίασης για εργαλεία δημιουργίας και παρακολούθησης περιβαλλοντικών εκθέσεων (Hilpert et al, 2014; Seidel, 2013), αναγνωρίζουν διάφορες προκλήσεις υλοποίησης που αντιμετωπίζουν τα συστήματα αυτά, όπως η ενοποίηση με υπάρχοντα συστήματα και η ανάκτηση δεδομένων σε πραγματικό χρόνο, και τονίζουν τη σημασία της ενοποίησης των πληροφοριών από διαφορετικές πηγές (El-Gayar & Fritz, 2006). Ωστόσο, οι μελέτες αυτές στερούνται βάθους ανάλυσης ως προς τις αρχές σχεδίασης τους και δεν σχετίζονται ρητά με τις συνθήκες του περιβάλλοντος εφαρμογής, όπως το επίπεδο της τεχνολογικής ωριμότητας, η διαθεσιμότητα των δεδομένων, η ανάκτηση και η ενοποίηση των δεδομένων ή ακόμη και τις οργανωτικές πτυχές που υπαγόρευσαν τη χρήση τους, και δεν αφορούν το πλαίσιο της εφοδιαστικής αλυσίδας. Επεκτείνοντας την έρευνα, οι ερευνητές πρέπει πέρα από την πραγματική σχεδίαση αυτών των συστημάτων να μελετήσουν σε πραγματικό περιβάλλον πώς αυτά τα συστήματα επιδρούν στην υλοποίηση περιβαλλοντικά βιώσιμων εφοδιαστικών αλυσίδων.

Ορμώμενη από τα παραπάνω, η διατριβή αυτή στοχεύει στο να προάγει τη γνώση στη σχεδίαση των συστημάτων διαχείρισης ενεργειακής κατανάλωσης και εκπομπών διοξειδίου του άνθρακα στην εφοδιαστική αλυσίδα. Εξετάζει εκείνους του περιβαλλοντικούς παράγοντες που σχετίζονται με την υλοποίηση αυτών των συστημάτων καθώς και το πώς αυτοί επηρεάζουν τη σχεδίασή τους. Επιπρόσθετα, συνιστά μια προσπάθεια για τη διερεύνηση των επιπτώσεων αυτών των συστημάτων στην ανάπτυξη περιβαλλοντικά βιώσιμων εφοδιαστικών αλυσίδων μέσω της μέτρησης της ενεργειακής κατανάλωσης και των εκπομπών διοξειδίου του άνθρακα (Butler, 2011), την υποστήριξη αποφάσεων με περιβαλλοντικά κριτήρια και την υλοποίηση βιώσιμων πρακτικών στην εφοδιαστική αλυσίδα (Seidel et al., 2013).

Λαμβάνοντας υπόψη το αντικείμενο της έρευνας και τα προαναφερθέντα ερευνητικά ερωτήματα, η Επίστημη της Σχεδίασης (Design Science) υιοθετήθηκε ως μεθοδολογική βάση αυτής της έρευνας καθώς είναι μια προσέγγιση που συνιστάται για την αντιμετώπιση ζητημάτων που αφορούν την περιγραφή μιας νέας κατηγορίας πληροφοριακών συστημάτων. Πιο συγκεκριμένα, χρησιμοποιήθηκε το μοντέλο που προτάθηκε από τους Peffers et al. (2007) ακολουθώντας μια σταδιακά αυξανόμενη προσέγγιση. Αυτό το μοντέλο συνέβαλε στην ανάπτυξη του τεχνουργήματος (artifact) και τη συστηματική διαμόρφωση των βασικών συστατικών της Θεωρίας Σχεδίασης του Πληροφοριακού Συστήματος (Information Systems Design Theory) (Gregor & Jones, 2007). Αρχικά ορίστηκε ο σκοπός και το αντικείμενο της σχεδίασης (purpose and scope). Στη συνέχεια, έγινε εξαγωγή μιας σειράς απαιτήσεων σχεδιασμού (design requirements) που καθοδήγησαν τις προδιαγραφές της σχεδίασης και εντοπίστηκαν οι βασικές έννοιες της θεωρίας (core constructs). Επιπλέον, αναπτύχθηκαν μια σειρά από προτάσεις (testable propositions) που αποτέλεσαν τη βάση και ελέγχθηκαν κατά τη φάση της αξιολόγησης. Χρησιμοποιώντας ως βάση τα παραπάνω, υπήρξε στενή συνεργασία με τις τέσσερις εταιρείες, προκειμένου να σχεδιαστούν και να αναπτυχθούν τα Συστήματα Διαχείρισης Ενεργειακής Κατανάλωσης και Εκπομπών Διοξειδίου του Άνθρακα και να ενημερωθούν τα επιμέρους συστατικά της θεωρίας (ο σκοπός και η εμβέλεια της θεωρίας (purpose and scope), οι απαιτήσεις σχεδίασης (design requirements), οι αρχές μορφής και λειτουργίας (form and function) και οι αρχές υλοποίησης (principles of implementation)). Στη συνέχεια, παρουσιάζονται τα δύο τεχνουργήματα και προτείνεται ένα σύνολο αρχών σχεδίασης και υλοποίησης. Συνοψίζοντας, τα δύο κύρια αποτελέσματα αυτής της διατριβής περιλαμβάνουν ένα τεχνούργημα (artifact) ενός Συστήματος Διαχείρισης Ενεργειακής Κατανάλωσης και Εκπομπών Διοξειδίου του Άνθρακα και μια Θεωρία Σχεδίασης Πληροφοριακών Συστημάτων που προδιαγράφει αυτή τη νέα κατηγορία των Πληροφοριακών Συστημάτων.

Η κατασκευή του τεχνουργήματος καθώς και η διαμόρφωση της θεωρίας σχεδίασης βασίζεται σε μια αυξητική και επαναληπτική προσέγγιση, όπου οι φάσεις της κατασκευής και της αξιολόγησης εναλλάσσονται (Markus et al., 2002). Πιο συγκεκριμένα, η επίδειξη και η αξιολόγηση σε πραγματικές συνθήκες διεξήχθη σε δύο φάσεις, έτσι ώστε η πρώτη φάση να μπορεί να ανατροφοδοτήσει το δεύτερο γύρο της σχεδίασης και της ανάπτυξης. Κατά τη διάρκεια αυτής της επαναληπτικής διαδικασίας, εντοπίστηκαν διάφορες προκλήσεις υλοποίησης που επιβάλλονται από τη διαθεσιμότητα των περιβαλλοντικών δεδομένων, τα διαφορετικά επίπεδα λεπτομέρειας των διαθέσιμων δεδομένων, την κακή ποιότητα των δεδομένων, τις εξαρτήσεις και τα προβλήματα συντονισμού λόγω της ανάγκης εναρμόνισης των εισροών πληροφορίας από διάφορους εταίρους, τα θέματα τεχνικής ενοποίησης και την απουσία μηχανισμών αυτοματισμού. Οι προκλήσεις αυτές αποκαλύπτουν τα ειδικά χαρακτηριστικά που πρέπει να υλοποιηθούν προκειμένου να διασφαλιστεί η αποτελεσματικότητα των συστημάτων αυτών σε ένα πραγματικό περιβάλλον. Ακολουθώντας αυτή τη διαδικασία, νέες αρχές σχεδίασης και υλοποίησης προήλθαν από την πραγματική υλοποίηση των τεχνουργημάτων, ενημέρωσαν τη θεωρία σχεδίασης και ενίσχυσαν την εγκυρότητά της.

Προκειμένου να διερευνηθεί η επίδραση των συστημάτων αυτών στο πεδίο εφαρμογής, η φάση της επίδειξης και της αξιολόγησης διεξήχθη χρησιμοποιώντας τη μελέτη πεδίου (field study) ως προσέγγιση σε τέσσερις διαφορετικές περιπτώσεις εταιρειών, οι οποίες καλύπτουν ένα ευρύ πεδίο διαχείρισης ενεργειακής κατανάλωσης και εκπομπών του διοξειδίου του άνθρακα που εκτείνεται από τον προμηθευτή των πρώτων υλών έως και το σημείο πώλησης. Οι περιπτώσεις μας περιλαμβάνουν δύο αντιπροσωπευτικές εταιρείες του κλάδου της κλωστοϋφαντουργίας που ενδιαφέρονται για την ενεργειακή απόδοση τους (ο κορυφαίος κατασκευαστής κλωστοϋφαντουργικών προϊόντων και μια διεθνής εταιρεία ενδυμάτων) και δύο αντιπροσωπευτικές εταιρίες του κλάδου των ταχέως κινούμενων προϊόντων που ενδιαφέρονται για τη βιωσιμότητα (μία αλυσίδα λιανεμπορίου και μία πολυεθνική εταιρία παραγωγής τροφίμων, παγκόσμιο ηγέτη στην κατηγορία της). Τα κύρια αποτελέσματα αυτής της διατριβής περιλαμβάνουν επίσης εμπειρικά στοιχεία που αποκαλύπτουν τις επιπτώσεις αυτών των συστημάτων στην ανάπτυξη περιβαλλοντικά βιώσιμων εφοδιαστικών αλυσίδων μέσω της μέτρησης της ενεργειακής κατανάλωσης και των εκπομπών διοξειδίου του άνθρακα, της υποστήριξης λήψης αποφάσεων με βάση περιβαλλοντικά κριτήρια και την υλοποίηση βιώσιμων πρακτικών στην εφοδιαστική αλυσίδα.

Ένα από τα βασικά χαρακτηριστικά αυτής της διατριβής είναι η διεπιστημονική φύση της, καθώς βασίζεται και συνυφαίνει τρεις διαφορετικούς κλάδους: Πληροφοριακά Συστήματα, Διοίκηση Λειτουργιών και Περιβαλλοντική Επιστήμη. Ως εκ τούτου, η θεωρητική συνεισφορά αυτής της διατριβής εκτείνεται σε αυτούς τους τρεις τομείς και επικεντρώνεται στα ακόλουθα ερευνητικά ρεύματα: Σχεδίαση Πληροφοριακών Συστημάτων, Πληροφοριακά Συστήματα για την επίτευξη Βιωσιμότητας και τη Διαχείριση της Ενεργειακής Κατανάλωσης και των Εκπομπών του Διοξειδίου του Άνθρακα. Η θεωρητική συνεισφορά της παρούσας διατριβής συνοψίζεται στα ακόλουθα:

- Σχεδίαση Πληροφοριακών Συστημάτων:

    1. *Η διαμόρφωση της Θεωρίας Σχεδίασης που προδιαγράφει τα Συστήματα Διαχείρισης Ενεργειακής Κατανάλωσης και Εκπομπών Διοξειδίου του Άνθρακα στην εφοδιαστική αλυσίδα.*
    2. *Ένα σύνολο αρχών σχεδίασης και υλοποίησης που συσχετίζουν τις γενικές προκλήσεις υλοποίησης της διαχείρισης της ενεργειακής κατανάλωσης και του διοξειδίου του άνθρακα με τον σχεδιασμό των συγκεκριμένων συστημάτων, έτσι ώστε να αναδειχθεί το πώς αυτές οι προκλήσεις επηρεάζουν τη σχεδίασή τους.*
    3. *Ο ορισμός των γενικών μοντέλων δεδομένων για τις βασικές οντότητες ανά πληροφοριακή ροή που απαιτούνται για τη διαχείριση της ενεργειακής κατανάλωσης και των εκπομπών του διοξειδίου του άνθρακα.*
    4. *Η βασιμότητα των εννοιών (proof-of-concept) μέσω δύο τεχνουργημάτων στην εφοδιαστική αλυσίδα, τα οποία παρέχουν πληροφορίες για το πώς το σύστημα λειτουργεί στην πράξη, τον τρόπο εφαρμογής του καθώς και αρχές για την αποτελεσματική εφαρμογή και τη χρήση του.*
    5. *Ένα υπόδειγμα εφαρμογής της ερευνητικής προσέγγισης της Επιστήμης της Σχεδίασης στη συγκεκριμένη περίπτωση συστημάτων στην εφοδιαστική αλυσίδα.*
    6. *Η χρησιμοποίηση μιας πιο ολιστικής προσέγγισης που συσχετίζει τα αποτελέσματα κάθε βήματος της ερευνητικής προσέγγισης της Επιστήμης της Σχεδίασης με τα συστατικά της Θεωρίας Σχεδίασης Πληροφοριακών Συστημάτων. Πιο συγκεκριμένα, δείχνουμε πώς η εφαρμογή της συγκεκριμένης προσέγγισης που προτείνεται από τους Peffers et al. (2007) μπορεί να υποστηρίξει την ανάπτυξη της θεωρίας και να συμβάλει στη διαμόρφωση των επιμέρους συστατικών της (Gregor & Jones, 2007).*

- Πληροφοριακά Συστήματα για την επίτευξη βιωσιμότητας

    7. *Διερεύνηση του ρόλου των πληροφοριακών συστημάτων για την ανάπτυξη περιβαλλοντικά βιώσιμων εφοδιαστικών αλυσίδων, εξετάζοντας σε βάθος την αναδυόμενη κατηγορία των Συστημάτων Διαχείρισης Ενεργειακής Κατανάλωσης και Εκπομπών Διοξειδίου του Άνθρακα και τη θέση τους στο ευρύτερο πλαίσιο των πληροφοριακών συστημάτων που αντιμετωπίζουν τις προκλήσεις βιωσιμότητας (ερευνητική περιοχή Green IS).*
    8. *Παροχή εμπειρικών δεδομένων σχετικά με το πώς αυτά τα συστήματα συμβάλλουν στην υλοποίηση περιβαλλοντικά βιώσιμων εφοδιαστικών αλυσίδων μέσω της υποστήριξης της διαχείρισης ενεργειακής κατανάλωσης και διοξειδίου του άνθρακα, τη λήψη αποφάσεων με περιβαλλοντικά κριτήρια και την εφαρμογή περιβαλλοντικά βιώσιμων πρακτικών στην εφοδιαστική αλυσίδα.*

- Διαχείριση της ενεργειακής κατανάλωσης και του διοξειδίου του άνθρακα

    9. *Οριοθέτηση της διαχείρισης της ενεργειακής κατανάλωσης και των εκπομπών του διοξειδίου του άνθρακα στην εφοδιαστική αλυσίδα, αναγνωρίζοντας διάφορες διαστάσεις διαχείρισης και τους αντίστοιχους απαιτούμενους δείκτες απόδοσης, πληροφοριακές ροές και δεδομένα.*

10. *Αναγνώριση των σημαντικών ζητημάτων και προκλήσεων υλοποίησης αυτών των συστημάτων κα παροχή εμπειρικών δεδομένων για την αντιμετώπισή τους.*
11. *Διερεύνηση του ρόλου τους στη στήριξη της Διαχείρισης της Ενεργειακής Κατανάλωσης και των Εκπομπών του Διοξειδίου του Άνθρακα στην εφοδιαστική αλυσίδα, παρουσιάζοντας το πώς μπορούν να συλλεχθούν, να επεξεργαστούν και να ενοποιηθούν τα απαιτούμενα δεδομένα προκειμένου να παρουσιαστούν με τη μορφή δεικτών απόδοσης (Key Performance Indicators, KPIs) από ένα τέτοιο σύστημα.*

Επιπρόσθετα, η παρούσα διατριβή παρέχει υποστήριξη σε μηχανικούς λογισμικού, σε εταιρείες παραγωγής λογισμικού και σε εταιρείες που θέλουν να εφαρμόσουν τέτοια συστήματα προκειμένου να καρπωθούν τα οφέλη διαχείρισης της ενεργειακής κατανάλωσης και του διοξειδίου του άνθρακα και την ανάπτυξη πιο βιώσιμων εφοδιαστικών αλυσίδων. Η προτεινόμενη θεωρία σχεδίασης και το τεχνούργημα που αναπτύχθηκε μπορεί να καθοδηγήσει τους μηχανικούς λογισμικού στις προσπάθειές τους να σχεδιάσουν τέτοιου τύπου συστήματα. Η προτεινόμενη εννοιολογική αρχιτεκτονική υποστηρίζει το διαχωρισμό σε επιμέρους κομμάτια λογισμικού (componentization), βελτιώνοντας έτσι την επαναχρησιμοποίηση του συστήματος και τις δυνατότητες ενσωμάτωσής του και παρέχοντας οφέλη τόσο για τους μηχανικούς όσο και για τους προμηθευτές λογισμικού. Επιπλέον, τα αναγνωρισμένα ζητήματα εφαρμογής (π.χ. δεδομένα και τεχνικά ζητήματα) και οι αντίστοιχες αρχές υλοποίησης μπορούν να αποτελέσουν κατευθυντήριες γραμμές υλοποίησης αυτών των συστημάτων και να διευκολύνουν τη διαδικασία εφαρμογής τους. Με τα αποτελέσματα αυτής της διατριβής σχετικά με τις επιπτώσεις τους, οι διαχειριστές της εφοδιαστικής αλυσίδας έχουν εμπειρικά στοιχεία σχετικά με τον αντίκτυπο τους που θα μπορούσαν να υποστηρίξουν τις μελλοντικές επενδυτικές τους αποφάσεις. Λαμβάνοντας υπόψη τα διάφορα επίπεδα διαχείρισης της ενεργειακής κατανάλωσης και των εκπομπών διοξειδίου του άνθρακα, οι διαχειριστές της εφοδιαστικής αλυσίδας μπορούν επίσης να προσεγγίσουν την υλοποίηση τους ως μια σταδιακή διαδικασία, υλοποιώντας τις διαστάσεις που υποστηρίζονται από την ωριμότητα της εταιρείας, τα μετρήσιμα δεδομένα και διαθέσιμα πληροφοριακά συστήματα και εργαλεία, καθώς και τα αναμενόμενα οφέλη.

ABSTRACT

Firms in several industries nowadays implement various practices in order to develop more environmentally sustainable supply chains, under the pressure of stricter regulatory requirements, energy costs' inflation, increasing requests of supply chain partners and mounting environmental awareness of consumers (Abbasi &Nilsson, 2012; Ashby et al., 2012; Sarkis et al., 2012; Srivastava, 2007). In this context, measuring and managing environmental impacts and, more specifically, the energy consumption and carbon emissions at the different stages of a supply chain, has been recognised as a main issue in the development of sustainable supply chains (Hervani et al., 2005; Lee, 2012; Seuring & Müller, 2008; Seuring & Gold, 2013; Veleva et al., 2003). Despite the fact that organizations have made continuous advances towards energy and carbon management, the benefits have not been fully exploited yet. The lack of standardized environmental performance measures that incorporate both environmental and non-environmental aspects, the absence of systems that gather non-traditional information relating to supply chain performance and the integration of these different types of information have been recognized as the most prevalent factors that lead to the low implementation of energy and carbon management (Hervani et al., 2005).

Moreover, the environmental data are either completely absent or merely available at high aggregation levels (Bjorklund et al., 2012; Melville & Whisnant, 2014; Veleva et al., 2003), thus preventing firms from accurately evaluating internal and external performance in environmental terms. While economic and operational data are available in internal systems, various integration issues regarding information technology remain to be tackled before incorporating both environmental and non-environmental aspects (El-Gayar & Fritz, 2006; Lee, 2003). Furthermore, in the realms of supply chain, streamlining the different types of supply chain parties (Hassini et al., 2012) and efficient information sharing and collaboration among supply chain partners must be effectively developed to enable an end-to-end information flow (Banker et al., 2006). The above suggest that the implementation of energy and carbon management in the supply chain is a challenging process and Information Systems (IS) have a strong potential by acting as a tool for managing energy and carbon across the supply chain (Dao et al., 2011; Melville, 2010).

Mindful of this potential, a new class of information systems emerges, the Energy and Carbon Management Systems (ECMS) (Melville & Whisnant, 2014, 2014). ECMS is a type of enterprise information systems that *"take as inputs various types of environmental data (e.g., electricity and fuel use, furnace combustion, emission factors, employee commuting, and air travel), process that data into usable information, (e.g., megajoules of energy, GHG emissions), and provide enhanced functionality (e.g., automated reporting, managerial dashboards, supply-chain analytics, and workflow management)"* (Melville & Whisnant, 2014, 2014). More specifically, these systems should be able to capture energy and carbon-related information from energy-consumption measurement infrastructures, integrate and interoperate with a company's existing enterprise systems (e.g., ERP), interpret and integrate the data received from various sources, and, finally, exchange data with the enterprise systems of supply chain partners. This kind of information systems are being rapidly adopted by firms (Liu & Stallaert, 2010) and represent a growing market that is projected to reach $5.7 billion by 2017 (Melville, 2012; Pike, 2011).

Except for supporting energy and carbon management, these systems are expected to impact the enablement of environmental sustainable supply chains by supporting the implementation of sustainable supply chain practices (Seidel et al., 2013) and enhancing environmental-aware decision-making and knowledge creation in terms of environmental

impacts within organizations (Butler., 2011; vom Brocke & Seidel, 2012; Seidel et al., 2013; Shrouf & Miragliotta, 2015).

Despite the growing interest for this kind of systems, there is little empirical knowledge on phenomena related to them (Melville, 2012), such as factors associated with their adoption, design guidelines or implementation issues that should be tackled (Melville, 2013). The major stream of research focuses on conceptualization and analysis of IS (Malhotra et al., 2013) and further work should be done on the rigorous artefact design, demonstration and evaluation (Malhotra et al., 2013, Melville, 2013; Seidel et al., 2013). Previous studies imply general design principles for environmental reporting and monitoring tools (Hilpert et al, 2014; Seidel, 2013), identify the different implementation challenges that these systems face, such as enterprise system integration and real-time data acquisition, and highlight the importance of integrating information from different sources (El-Gayar & Fritz, 2006). However, these studies remain rather superficial in their design principles, which remain non-explicitly related to contextual implementation settings, such as the level of technological maturity, data availability-acquisition and integration, or even the organizational aspects motivating the use of such tools and not take into account the supply chain context. Going a step further, researchers must not only work on the actual design of these systems but also establish the "in-field" impact, in order to investigate how these systems impact the implementation of environmentally-sustainable supply chains.

Motivated by the above, this research aims at advancing the design of energy and carbon management systems in the supply chain and elaborating on the contextual implementation settings that affect their design. Moreover, it presents an effort to investigate the impact of these systems on the implementation of environmentally sustainable supply chains, by measuring energy and carbon emissions, supporting environmental-aware decision-making in the supply chain (Butler, 2011) and sustainable supply chain practices (Seidel et al., 2013).

Given the aforementioned research objective and research questions, we adopt the design science paradigm as methodological backbone, as it is a recommended approach for addressing the issues related with the prescription of a new class of information systems such as Energy and Carbon Management Systems. The 'design-science research methodology process model' (Peffers et al., 2007) is used, contributing to the development of the ECMS artifact and the systematic formulation of the basic components of ISDT (Gregor & Jones, 2007) based on an incremental approach. More specifically, initially we define the design's purpose and scope. Then we derive a set of design requirements from justificatory knowledge, which give guidance to the subsequent specification of the design, and we identify the theory's core constructs. Moreover, we develop a set of testable propositions that inform the evaluation of the proposed design and which we test during the evaluation step. By using as starting point the above, we work closely with four companies in order to design and develop Energy and Carbon Management System artifacts and to inform the theory's purpose and scope, design requirements, principles of form and function, and core constructs. Subsequently, we demonstrate the two artifacts, concluding with a set of design and implementation principles that inform form and function and components of the design theory. To sum up, the two main outcomes of this thesis include an ECMS artifact and an Information Systems Design Theory for ECMS that prescribes this new class of Information Systems.

The artifact generation and the ISDT formulation is based on an incremental and iterative refinement approach that switches between construction phases and evaluation (Markus et al., 2002). More specifically, Demonstration & Evaluation in real-world settings was conducted in two phases, so that the first phase could give feedback to the second round of design and development. During this iterative process, a list of implementation challenges have been identified, imposed by the environmental data availability, the different data granularity levels, the poor data quality, the dependencies and coordination problems due to the need of aligning inputs from multiple partners, the technical integration issues and the absence of automation mechanisms. Evidently, these challenges reveal specific features to be implemented in order to ensure the efficacy of such systems in a real-world context. By following this process, new design and implementation principles have derived from the actual implementation of the artifacts, to inform ISDT components and enhance its validity.

In order to investigate the in-field impact of an ECMS, we conducted the demonstration and evaluation phase by employing a field study in four different cases that cover a broad scope of the energy and carbon management, ranging from the supplier of raw materials to the point of sales. Our cases include two representative textile organizations interested in energy-efficiency (a leading textile manufacturer and an international clothing company) and for supply chain issues with two representative fast-moving-consumer-goods (FMCG) organizations interested in sustainability (a retailer and a multinational food manufacturer, global leader in its domain). The final main outcomes of this thesis also include empirical evidence that reveals the impact of ECMS on the enablement of environmentally-sustainable supply chains, through the measurement of energy and carbon emissions, the support of environmental-aware decision-making and the implementation of sustainable supply chain practices.

One of the main strengths of this thesis is its interdisciplinary nature, as it interweaves three different disciplines: Information Systems (IS), Operations Management and Environmental Science. Therefore, the contribution of this thesis from a theoretical perspective is found across these three disciplines and focuses on the research streams of IS Design, IS for Sustainability and Energy and Carbon Management. The contributions of this thesis are summarized in the following list:

- IS Design:
  1. *The formulation of an Information Systems Design Theory (ISDT) that prescribes Energy and Carbon Management Systems in the Supply Chain.*
  2. *A set of design and implementation principles that correlate generic energy and carbon management implementation challenges with the design of ECMS, in order to show how these challenges affect the ECMS Design.*
  3. *The definition of generic data-models describing the information flows that are required for Energy and Carbon Management.*
  4. *A proof-of-concept (two artifacts) for Energy and Carbon Management Systems in the supply chain, that provide insights into how ECMS operate in practice, how they are implemented, and recommendations for their effective implementation and use.*
  5. *Providing an exemplar of applying the Design Science research approach in the case of ECMS in the supply chain.*
  6. *Using a more holistic approach that correlates the outcomes of each step of the Design Science approach with the components of the ISDT theory. More specifically, we show how the application of the 'design-science research methodology process model' suggested by Peffers et al. (2007) could support the development of the ISDT theory and inform its respective components (Gregor & Jones, 2007).*
- IS for Sustainability
  7. *Explore the role of IS on the development of environmental sustainable supply chains by investigating in-depth the emerging class of ECMS and position them in the broader context of information systems addressing sustainability challenges (Green IS research area).*

8. *Provide empirical evidence on how ECMS contribute to the implementation of environmentally sustainable supply chains, by supporting energy and carbon management, environmental-aware decision making and the implementation of environmentally-sustainable supply chain practices.*

- Energy and Carbon Management

9. *Frame the Energy and Carbon Management in the supply chain, by identifying a set of various dimensions related to them and the respective Key Performance Indicators (KPIs), information flows and required data.*
10. *Identify important Energy and Carbon Management implementation issues and challenges and provide empirical evidence on how to address them.*
11. *Explore the role of IS on supporting Energy and Carbon Management in the Supply Chain, by presenting how the required energy and carbon management data can be collected, integrated, processed and presented in the form of KPIs by an ECMS.*

On the other hand, this thesis offers support to software engineers/ developers and vendors and organizations want to implement ECMS aspiring energy and carbon management benefits and more sustainable supply chains. The suggested ECMS design theory and the developed artifact can inform software engineers in their efforts to design IS to be used for energy and carbon management in the supply chain. Furthermore, the suggested conceptual model supports componentization and can improve the reusability and integration of the systems, providing benefits for both software engineers and software vendors. Moreover, the identified implementation issues (e.g. data and technical) and the respective implementation principles could constitute ECMS implementation guidelines and facilitate the implementation process. With the outcomes of this thesis regarding the impact of the ECMS, supply chain managers have empirical evidence on the impact of ECMS that could support their future investment decisions. With the various levels of energy and carbon management identified, the supply chain managers can approach the implementation of ECMS as a gradual process, by implementing the energy and carbon management dimensions that are more aligned with the company maturity, measurable data, available information systems and tools, as well as the expected benefits.

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LIST OF ABBREVIATIONS

TERMS	**ABBREVIATIONS**
Advanced Planning and Scheduling	APS
Building Management Systems	BMS
Carbon Dioxide	CO_2
Carbon Dioxide Equivalent	CO_2e
Contextual Information Flow	CI
Decision Science Research	DSR
Direct Energy	DE
Energy and Carbon Management Systems	ECMS
Enterprise Resource Planning	ERP
Environmental Information Flow	EC
Environmental Management Information Systems	EMIS
Environmental Product Declaration	EPD
Fast Moving Consumers Goods	FMCG
Global Reporting Initiative	GRI
Green House Gas	GHG
Green Supply Chain Management	GrSCM
Indirect Energy	IE
Information Systems	IS
Information Technology	IT
International Organization for Standardization	ISO
IS Design Theory	ISDT
Key Performance Indicator	KPI
Life Cycle Assessment	LCA
Life Cycle Inventories	LCI
Manufacturing Execution System	MES
Product Data Management	PDM
Product Environmental Information Flow	PEIF
Stock Keeping Unit	SKU
Sustainability Performance of Supply Chains	SPSC
Sustainable Supply Chain Performance Measurement	SSCPM
Sustainable Supply Chain management	SSCM
Transactional information flow	TI
Warehouse Management Systems	WMS

1 INTRODUCTION

1.1 Research Motivation

Climate change has undoubtedly become one of the most critical problems that humanity needs to address in the years to come. As the future of our ecosystem and society is dependent on our ability to reverse or limit the effects of global climate change, sustainability issues have come to the societal and governmental forefront (Watson et al., 2010). Firms have taken steps in incorporating the principles of sustainability into their operational processes, into their long- and short- term decision-making and then into their long term corporate strategy. However, sustainability is an issue that extends beyond the boundaries of a single firm (Seuring & Gold, 2013).

Consequently, Green supply-chain management (GrSCM) or sustainable supply-chain management (SSSM) has received substantial attention over the last years by researchers and practitioners alike. Sustainable supply chain management (SSCM) has many definitions (Ahi & Searcy, 2013). It can be defined as "integrating environmental thinking into supply-chain management, including product design, material sourcing and selection, manufacturing processes, delivery of the final product to the consumers as well as end-of-life management of the product after its useful life" (Srivastava, 2007). According to Seuring & Muller (2008), SSCM is defined as “the management of material and information flows as well as cooperation among companies along the supply chain while taking into account all three dimensions of sustainable development, i.e. economic, environmental and social". An extensive list of literature reviews on SSCM highlights the growing interest for SSCM for both academia and practitioners (e.g. Abbasi &Nilsson, 2012; Ashby et al., 2012; Carter & Rogers, 2008; Carter & Easton, 2011; Gimenez & Tachizawa, 2012; Sarkis et al., 2011; Seuring & Muller, 2008; Srivastava, 2007).

Earlier efforts indicate that the greening of supply chains could be materialized by implementing various green supply chain practices (Hervani, 2005). These practices may range from green product design (Allenby, 1993; Chu et al., 2009), green procurement (e.g. choosing suppliers based on environmental criteria, purchasing environmental-friendly raw materials/products) (Govindan et al., 2015; Handfield et al., 2002; Tate et al., 2012), manufacturing practices (Schrettle et al., 2014) and product end-of-life practices (e.g. reduction, reuse, remanufacturing, recycling (Hervani, 2005). However, a significant percentage of environmental impacts in the supply chain come from a firm's supply chain processes and products. Therefore, these practices could be also discriminated to internal and external ones based on the required level of cooperation with the partners for their implementation (Zhu, et al., 2013).

Increasing advances in developing more green supply chains have raised the issue of measuring environmental impacts at the different stages of a supply chain (Hervani et al., 2005; Veleva et al. 2003; Seuring & Müller, 2008; Seuring & Gold, 2013). As a result, measuring and monitoring such impacts form the basis for controlling the environmental performance of supply chain processes, making environmental-aware decisions based on improved measures and tracking the progress in environmental performance.

A growing body of academic literature discusses environmental performance measurement issues in supply chain management (Hervani et al., 2005; Schaltegger & Burritt, 2014; Tattichi et al., 2013). As the identification of the performance metrics is a critical aspect of the environmental performance measurement, the literature also proliferates of studies on the environmental performance measurement focusing on metrics (Ahi & Searcy, 2014; Bai et al., 2012; Bai & Sarkis, 2014; Chae, 2009). Given the extensive listing of environmental performance metrics, the energy consumption and carbon emissions has been recognized as the most prominent (Ahi & Searcy, 2014; Varsei et al., 2014) due to their significant consequences on environment, their relation to energy costs and the several emission-control regulatory policies. Therefore, another stream of research focuses mainly on the energy and carbon management within the context of supply chain. (e.g. Bunse et al., 2011; Lee, 2012; Shrouf & Miragliotta, 2015)

Despite the fact that organizations have made continuous advances towards energy and carbon management, the benefits have not been fully exploited yet. The lack of standardized environmental performance measures that incorporate both environmental and non-environmental aspects, the absence of systems that gather non-traditional information relating to supply chain performance and the integration of the different types of information have been recognized as the most prevalent factors that lead to the low implementation of energy and carbon management (Hervani et al., 2005).

Moreover, the environmental data are either completely absent or merely available at high aggregation levels (Bjorklund et al., 2012; Melville & Whisnant, 2014; Veleva et al., 2003), thus preventing firms from accurately evaluating internal and external performance in environmental terms. While economic and operational data are available in internal systems, various integration issues regarding information technology remain to be tackled before incorporating both environmental and non-environmental aspects (El-Gayar & Fritz, 2006; Lee, 2003). Furthermore, in the realms of supply chain, aiming to streamline the different types of supply chain parties (Hassini et al., 2012), efficient information sharing and collaboration among supply chain partners must be effectively developed to enable an end-to-end information flow (Banker et al., 2006). The above suggest that the implementation of energy and carbon management in the supply chain is a challenging process.

Within this context, Information Systems (IS) have a strong potential by acting as a tool for managing energy and carbon across the supply chain and thus pinpointing areas for improvement and savings. Moreover, they could be the basis for supporting the development of more sustainable supply chain processes and products. Previous research studies have discussed the critical role of IS in the greening of supply chains (Dao et al., 2011; Melville, 2010). IS can enable firms to standardize, monitor, capture, and utilize data and metadata that help firms measure and evaluate internal and external performance in both financial and environmental terms (Björklund et al., 2012; Dao et al., 2011; Hervani et al., 2005; Melville, 2010). In the realms of supply chain, they should also facilitate both collaboration and information exchange by improving information flows among supply chain partners (Banker et al., 2006).

Mindful of this potential, a new class of information systems emerges, the Energy and Carbon Management Systems (ECMS) (Melville & Whisnant, 2014). ECMS is a type of enterprise IS that "takes as inputs various types of environmental data (e.g., electricity and fuel use, furnace combustion, emission factors, employee commuting, and air travel), processes that data into usable information, (e.g., megajoules of energy, GHG emissions), and provides enhanced functionality (e.g., automated reporting, managerial dashboards, supply-chain analytics, and workflow management)" (Melville & Whisnant, 2014, 2014). More specifically, these systems are required to capture energy and carbon related information from energy consumption measurement infrastructures and collect and analyze operational data sets from a company's existing enterprise systems (e.g., ERP) or even its supply chain partners enterprise systems. Then, these systems integrate environmental with other information flows in order to calculate and monitor both the environmental and traditional performance indicators of processes and products. This kind of information systems are being rapidly adopted by firms (Liu & Stallaert, 2010) and represent a growing market that is projected to reach $5.7 billion by 2017 (Melville, 2012; Pike, 2011).

Despite the increasing interest on these systems, the business and academic studies that discuss specifically their design are limited over the last few years. These studies adopt mainly the Design Science Approach, in order to shed light on the design process, and then develop and evaluate the respective artifact (Bensch et al., 2014; Graeuler et al., 2013; Hilpert et al., 2011). Previous contributions suggest the need for insights into how ECMS operate in practice, how they are implemented, and recommendations for their effective implementation and use (Watson et al. 2010; Melville 2010). Therefore, further research is needed regarding the actual design and implementation of such systems in a real-world context (Malhotra et al., 2013; Seidel et al., 2013).

Except for supporting energy and carbon management, these systems are expected to impact the enablement of environmental sustainable supply chains by supporting sustainable supply chain practices implementation (Seidel et al., 2013) and enhancing environmental-aware decision-making and knowledge creation within organizations (Butler., 2011; vom Brocke & Seidel, 2012; Seidel et al., 2013; Shrouf & Miragliotta, 2015). For example, Stindt (2014) employed a design science approach for an Environmental Management Information System that helps firms to improve decision-making processes in the reverse logistics. According to Loeser (2013), they are meant not to contribute to sustainability directly but rather provide transparency and be a foundation for decision-making that supports the transition to eco-friendly business practices.

Bridging the excitement and motivation of the abovementioned challenges, this research aims at advancing the design of energy and carbon management systems in the supply chain and elaborating on the contextual implementation settings that affect their design. Moreover, it presents an effort to investigate the impact of these systems on the implementation of environmentally sustainable supply chains.

1.2 Research Objective & Approach

Considering the above, the starting point of this research is on advancing the understanding of “how” to design and implement energy and carbon management system in the supply chain and it aims to shed light on ECMS' impact on the development of environmentally sustainable supply chains.

More specifically, the following questions arise:

- Which are the business requirements for energy and carbon management in the supply chain?
- Which are the information flows needed in order to support energy and carbon management in the supply chain?
- Which are the design requirements for energy and carbon management in the supply chain?
- How can energy and carbon management systems integrate the information flows needed in order to support energy and carbon management?
- Which are the necessary system components that specify energy and carbon management systems?
- Which are the design and implementation principles that should guide the design and implementation of energy and carbon management systems?

- How does the design of energy and carbon management systems support energy and carbon management?
- How does the design of energy and carbon management systems support environmental - aware decision-making and the implementation of environmentally - sustainable supply chain practices?

Given that the aim of this thesis is to provide answers regardless of the application domain of energy and carbon management systems, we also investigate the effect of contextual implementation challenges, such as data quality and availability, data capture and integration, environmental performance metrics and collaboration and information sharing on the design of these systems. Therefore, we conclude to two more questions:

- Which contextual factors affect the design and implementation of energy and carbon management systems?
- How do the contextual factors affect the design and implementation of energy and carbon management systems?

Given our research objective and the aforementioned research questions, we adopt as methodological backbone the Design Science paradigm. This approach is recommended for addressing issues related to the prescription of a new class of information systems, such as the Energy and Carbon Management Systems. More specifically, we use the 'design-science research methodology process model' (Peffers et al., 2007) (Presented in detail in Section 3.2). The outcome of a decision science research (DSR) study could be both an artifact and an IS design theory (ISDT) (Kuechler & Vaishnavi, 2012). ISDT, as introduced by Walls et al. (1992,2004), is a set of primarily prescriptive statements describing how a class of artifacts should behave and how they can be constructed. Particularly in an emergent field as Energy and Carbon Management Systems both an exemplar artifact and an ISDT is important to offer theory-based guidance for their design to researchers and practitioners alike, as well as implementation guidelines. Therefore, we use the specification framework for ISDT suggested by Gregor & Jones (2007) where they have expanded the initial Walls et al., (1992) approach by incorporating the notion of artifact instantiation. More specifically, they propose eight separate components of design theories: (1) purpose and scope, (2) constructs, (3) principles of form and function, (4) artifact mutability, (5) testable propositions, (6) justificatory knowledge (kernel theories), (7) principles of implementation, and (8) an expository instantiation (presented in detail in Section 3.3).

The artifact generation is concrete, based on an incremental and iterative refinement approach that switches between construction phases and evaluation (Markus et al., 2002). More specifically, the Demonstration & Evaluation step in real-world settings is conducted in two phases so that the first phase could give feedback to the second round of objectives definition and the design and development. During this iterative process, we identify new design and implementation principles derived from the actual implementation of the artifacts, to inform ISDT components and enhance its validity. This round is strongly guided by the implementation challenges imposed by the environmental data availability, the different data granularity levels, the poor data quality, the dependencies and coordination problems due to the need of aligning inputs from multiple partners, the technical integration issues and the absence of automation mechanisms. Evidently, these challenges reveal specific features to be designed and implemented in order to ensure the efficacy of such systems in a real-world context.

For collecting data for the various steps of Design Science Research Steps, four different case studies are used. The Energy and Carbon Management is recommended to be handled separately for manufacturing and for warehousing and transportation activities, as this allows for analysis and details focused on the specific activities of each supply chain. Therefore, two of these cases cover manufacturing activities and represent the textile industry and the other two cover warehousing and transportation activities and represent the Fast Moving Consumer Goods Industry (FMCG). Their specificities are also discussed in this chapter (Section 3.4.2). Moreover, we conduct the demonstration and evaluation phase by employing a field study and using the aforementioned companies as our context.

Summarizing the above, the main research questions of this thesis are formulated as following:

- Q1. What is the design of energy and carbon management systems in the supply chain?
- Q2. How do energy and carbon management systems impact the development of environmentally-sustainable supply chains?

A Design Science research approach is employed and the expected outcome is both an artifact and an Information Systems Design Theory for Energy and Carbon Management Systems. Figure 1.1 depicts the methodology employed in this research and the specific steps that Peffers et al., (2007) proposed, the research outcomes of each one of these steps and the resulting ISDT for ECMS. More specifically, Figure 1.1 shows that the research was conducted in a three-year period and the five steps of DSR approach have been conducted separately for manufacturing and for warehousing and transportation cases, by following an iteration approach (Design Science Research Methodology Process level in Figure 1.1). Each one of these steps has a specific set of results (Design Science Research Process Outcomes level in Figure 1.1) that also contributes to the systematic formulation of the basic components of ISDT (ECMS Theory Components level in Figure 1.1) based on an incremental approach.

Below, we summarize how the ISDT was formulated, following these steps. Initially, we define the design's purpose and scope. Then we derive a set of design requirements from justificatory knowledge that give guidance to the subsequent specification of our design and we identify the theory's core constructs. Moreover, we develop a set of testable propositions that inform the evaluation of the proposed design and which have been tested during the evaluation step. By using as starting point the above, we work closely with four companies in order to design and develop Energy and Carbon Management System artifacts and to inform the theory's purpose and scope, design requirements, principles of form and function, core constructs and deploy an instantiation of ECMS. Subsequently, we demonstrate the two artifacts and concluding to a set of design and implementation principles that inform principles of form and function and principles of implementation components of design theory. We conclude by discussing the mutability aspect of the design theory in Section 7.2.

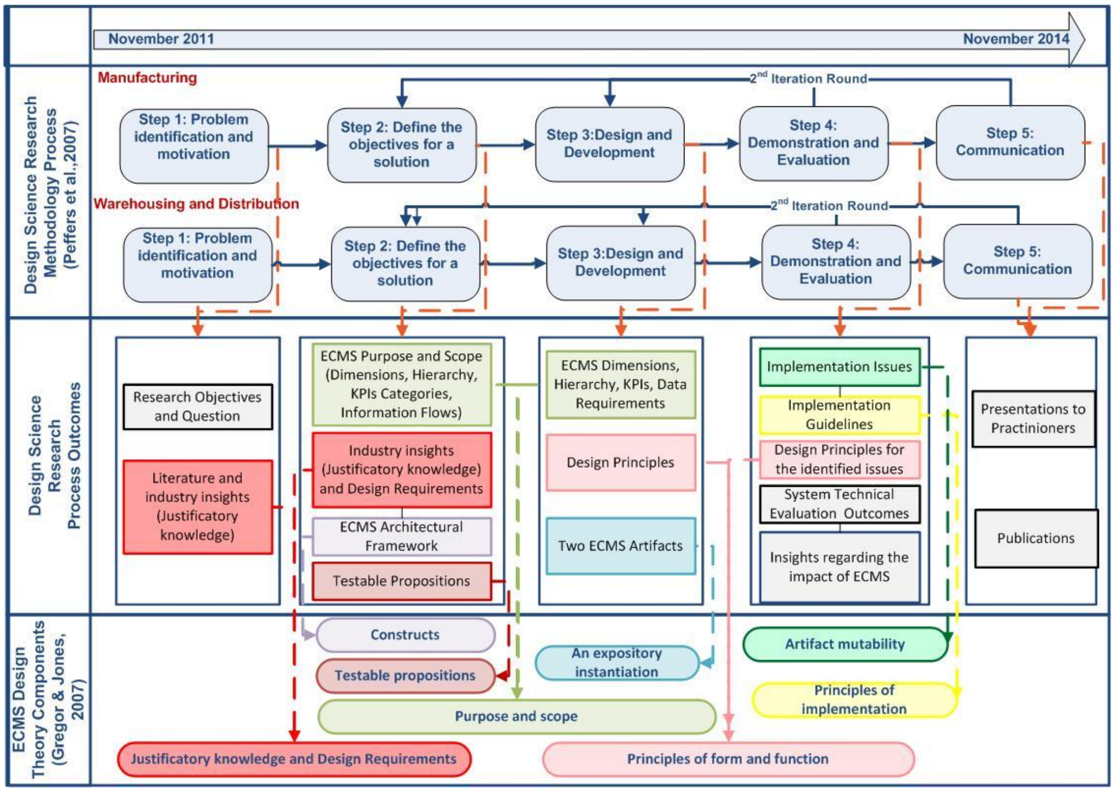

Figure 1.1: Research Methodology and Research Outcomes

1.3 Thesis Outline

There are seven (7) chapters that constitute this dissertation as follows:

- Chapter 1 (Introduction)

This chapter introduces the readers to the main concepts of this research, i.e. sustainable supply chain management, energy and carbon management and energy and carbon management systems. Simultaneously, it communicates the research's motivation, as well as the key research question. Last, but not least, this chapter details the research plan/strategy, according to which the research question are answered.

- Chapter 2 (Research Background)

It is critical to be cognizant of the rationale for the relevance of the work. Therefore, an industrial exploratory research, an extensive literature review and an industry survey have been used as tools for highlighting the significance of this study and conclude with the main research objectives and questions. Thus, this chapter presents initially the industrial exploratory research and then draws upon literature from three research streams ('Environmental Performance Measurement', 'Green Information Systems' and Environmental Management Information Systems'), that provide the theoretical and methodological basis. Moreover, the outcomes of the industry survey regarding the impact of Energy and Carbon Management Systems are discussed. Finally, we conclude with the main research objective and questions as drawn from both the literature review and the outcomes of the preliminary research.

- Chapter 3 (Research Methodology)

The aim of this chapter is to present the research methodology employed in order to address the research objectives and answer the research questions. Given our research objective and the aforementioned research questions, we adopt as methodological backbone the Design Science paradigm (Baskerville et al., 2015) and we consider both an artifact and an information systems design theory (ISDT) as outcomes of this study. Thus, initially we present the 'design-science research methodology process model' (Peffers et al., 2007). Then, we present the specification framework for ISDT suggested by Gregor & Jones (2007) and components of an ISDT in detail. For collecting data for the various steps of Design Science Research steps, four different cases studies are selected and presented. Energy and Carbon Management in the supply chain is handled separately for manufacturing and for warehousing and transportation activities, as this allows for analysis focused on the specifics of each supply chain. Therefore, two of these cases cover manufacturing activities and represent the textile industry and the other two cover warehousing and transportation activities and represent the Fast Moving Consumer Goods Industry. Their specificities are also discussed in this chapter.

- Chapter 4 (Design and Development of Energy and Carbon Management Systems)

This chapter presents initially the need for developing energy and carbon management in the supply chain and defines the various objectives and scopes, as well as a set of testable propositions regarding their impact. Then, a general set of design requirements for energy and carbon management systems are proposed, deriving a general set of system components. These components are incorporated in a conceptual high-level architectural framework that aims to specify in a more abstract level the system components that this new class of information systems includes. Even though the architectural framework is context-independent and technology independent, contextual implementation settings may affect the design of these systems and lead to new requirements and the respective system functionalities that will cover them. Therefore, the chapter presents some of the contextual settings that may affect the design of such systems. We conclude by presenting a set of testable propositions that guide their evaluation.

- Chapter 5 (Evidence from Demonstration and Evaluation in Manufacturing)

The aim of this chapter is to present how the proposed Energy and Carbon Management System artifact has been designed, developed and deployed in two cases studies in the manufacturing sector. Having as starting point the outcome of Section 4, we elucidate ECMS in the context of manufacturing by capturing and presenting more precise user requirements, data requirements and KPIs. Then, we specify the components that incorporate these requirements, the architecture of the artifact and the design principles of each component. Then, we describe the exact real-case settings under which we implemented the two systems and the implementation. The step of evaluation is conducted in two phases, so that the first phase could give feedback to the second round of design and development. The first round revealed a set of challenges imposed e.g. by the limited environmental data availability that are presented. Evidently, these challenges reveal specific design and implementation principles to be taken into account, in order to ensure the efficacy of such systems in a real-world context. We conclude by providing evidence regarding the impact of these systems on the implementation of environmentally sustainable supply chains by supporting energy and carbon management, environmental-aware decision making and the implementation of environmentally sustainable supply chain practices.

- Chapter 6 (Insights from Demonstration and Evaluation in Warehousing and Distribution)

The aim of this chapter is to present how the Energy and Carbon Management System artifact has been designed, developed and deployed in the warehousing and distribution areas of two cases in the FMCG sector. The structure and the content of this chapter are similar to Chapter 5.

- Chapter 7 (Discussion and Conclusions)

This final chapter overviews the main outcomes of this research. Then, it presents and discusses the research's contribution to theoretical knowledge along with its practical value. At the end of this chapter, the research limitations are pointed out and avenues for further research are recommended. Finally, the thesis includes a set of six (6) Appendices A to F that complement the chapters.

The following figure presents the chapters (right) and the respective outcomes by taking into account the Design Science Research Process Outcomes (middle) with respect to the research methodology (left).

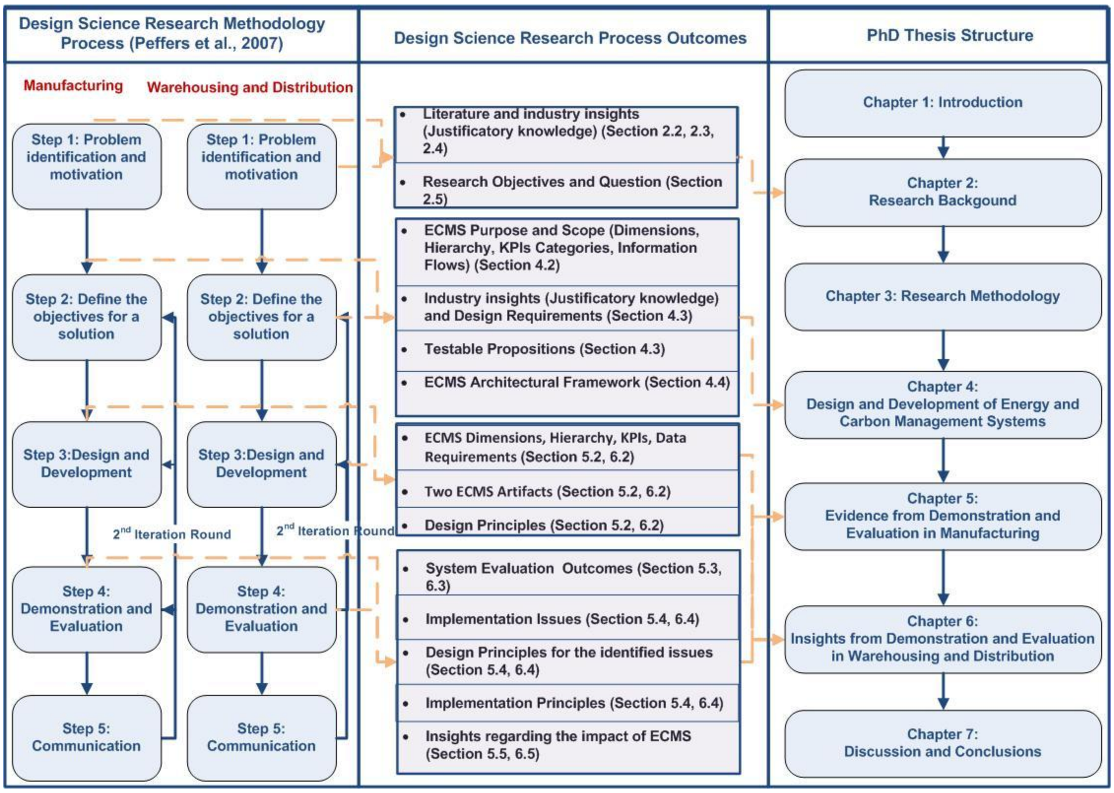

Figure 1.2: Thesis Structure (Left: Research Methodology, Middle: Design Science Research Process Outcomes, Right: PhD Thesis Chapters)

Moreover, the following figure presents the chapters and the outcomes by taking into account the ISDT components per chapter.

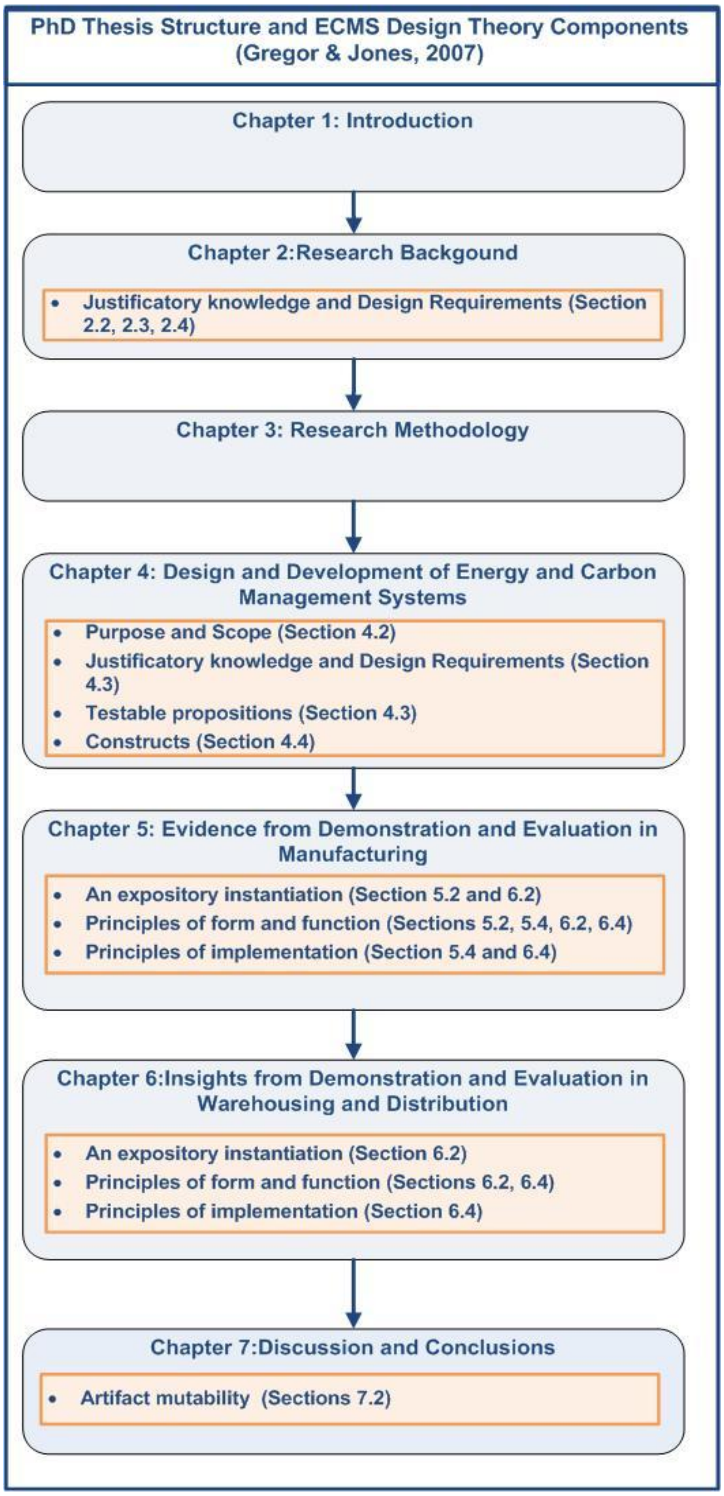

Figure 1.3: PhD Thesis Chapter and the respective ECMS Theory Components

To support reading comprehension, the following table shows each research question in accordance with the chapter where the answer is discussed.

Table 1.1: Research Questions in accordance with the Thesis Structure

Questions	Sections
Which are the business requirements for energy and carbon management in the supply chain?	4.2, 5.2, 6.2
Which are the information flows needed in order to support energy and carbon management in the supply chain?	4.2
How can energy and carbon management systems integrate the information flows needed in order to support energy and carbon management?	4.4
Which are the necessary components that specify energy and carbon management systems?	4.4
Which are the design and implementation principles that will guide the design and implementation of energy and carbon management systems?	5.2, 6.2
Which contextual factors affect the design and implementation of energy and carbon management systems?	5.4, 6.4
How do the contextual factors affect the design and implementation of energy and carbon management systems?	5.4, 6.4
How does the design of energy and carbon management systems support energy and carbon management?	5.5, 6.5
How does the design of energy and carbon management systems support environmental - aware decision-making and the implementation of environmentally sustainable supply chain practices?	5.5, 6.5

2 RESEARCH BACKGROUND

2.1 Introduction

It is critical to be cognizant of the rationale for the relevance of the work. Therefore, an industrial exploratory research, an extensive literature review and an industry survey have been used as tools for highlighting the significance of this study and conclude with the main research objectives and questions. Thus, this chapter presents initially the industrial exploratory case study (Section 2.2) and then draws upon literature from three research streams that provide the theoretical and methodological basis. In Section 2.3 we provide a literature review on Environmental Performance Measurement, Green Information Systems and Energy Management Information Systems. Moreover, the outcomes of the industry survey regarding the impact of Energy and Carbon Management Systems are discussed in Section 2.4. Finally, in Section 2.5, we conclude with the main research objectives and questions.

2.2 Industrial Exploratory Research on Energy and Carbon Management in the Supply Chain

2.2.1 Introduction

The aim of this chapter is to shed light on the issues that are related with energy and carbon management in the supply chain. By leveraging the empirical knowledge gained towards a series of meetings with industrial experts and an industry survey, we identify the main challenges and gaps that could be addressed in the supply chain and the motivation behind this.

2.2.2 Context and Approach

Nowadays, firms in various industries start to feel the need to improve their environmental performance and energy efficiency under the pressure of both inside and outside forces including consumers, international protocols and regulatory bodies, supply chain partners, employees, and shareholders. Many firms have applied various practices in order to address their environmental challenges and they have started to integrate environmental thinking into their supply chain. One of the prominent practices is related to measuring and managing the energy consumption and carbon emissions across the supply chain. In this context and by taking into account the overall challenges, the Efficient Consumer Response (ECR) organization, a joint trade and industry body launched in 1994 to make the FMCG sector as a whole more responsive to consumer demand and promote the removal of unnecessary costs from the supply chain, has initiated an ECR project titled "Environmental Sustainability and Carbon Footprint Monitoring". An ECR project is the mechanism used by the ECR organization in order to involve its members (retailers and manufacturers) into discussions under a common agenda with the objective to define best practices.

The specific ECR project was initiated in November 2012 in Greece. This ECR project ran till December 2012. The members of the group have been supply chain or logistics managers or directors of the following companies: Barilla, METRO, Beiersdorf, Colgate-Palmolive, Nestle, Procter & Gamble, Unilever, Delhaize, Kassoudakis Logistics Partner, KPMG and Planning Supply Chain Consultants. The main objective of this ECR project was to investigate the current level of adoption and future interest in energy and carbon management, to examine the approaches followed in measuring and managing the energy and carbon emissions and to reveal the main challenges and directions on these issues. The ECR project entailed monthly meetings of industry partners on a voluntary basis where various issues, presented in Table 3.1 were discussed. Besides, a short scale application of an energy and carbon management approach based on actual data was conducted in order to reveal any application difficulties and challenges. Moreover, an industry survey was conducted in order to capture the general trends regarding sustainability and energy and carbon management in the supply chain. The outcomes of both industry survey and the application of energy and carbon management were discussed and validated with the members of the group.

Table 2.1: "Environmental Sustainability and Carbon Footprint Monitoring" Project Agenda

Date of Meeting	**Meeting Agenda**
22 Nov 2011	Project brief and objectives
14 Dec 2011	Industry survey on Energy Efficiency and CO_2 monitoring Discussion on Energy Efficiency and CO_2 KPI's
24 Jan 2012	Review of industry survey questionnaire Discussion on the methods used by each company for Energy Efficiency and CO_2 monitoring Definition of common KPI's
19 Mar 2012	Presentation of initial industry survey results Discuss current standards for Energy Efficiency and CO_2 monitoring First discussion on information sharing requirements among supply chain partners
24 Apr 2012	Comments on information sharing requirements among supply chain partners Definition of common KPI's Discussion on pilots to validate the KPI's
22 May 2012	Presentation of first results evaluating alternative measurement methods based on the data of one retailer Discussion on the common KPI's
20 Jun 2012	Presentation of detailed results evaluating alternative measurement methods based on the data of one retailer Comparison to approaches of other initiatives, such as Green Freight Europe and COFRET

In the following sections, we present the research design of the industry survey and the application of the environmental performance measurement.

2.2.3 Industry Survey

The industry survey had the following individual objectives:

- To investigate the current level of adoption and future interest in environmental practices and in energy and carbon management.
- To examine the approaches followed in measuring and managing energy consumption and carbon emissions and to what extent these approaches are applied.

- To examine the level of collaboration on addressing environmental issues.
- To examine the data availability required in order to support energy and carbon management.
- To examine if firms are ready to support information systems solutions that enable energy and carbon management both inside an organization and in the supply chain.

In order to address the aforementioned objectives, the questionnaire was selected as the research instrument. The questionnaire (see Appendix A) includes three main sections: Environmental Practices, Organization's environmental and communication strategy, Energy and Carbon Management and Collaboration, and Reasons for Implementing Environmental Business Practices. The measures employed in the questionnaire study have been adapted from the extant literature and include various concepts such as environmental corporate strategy, environmental information sharing. The industry survey was conducted at European level and was supported by the Efficient Consumer Response (ECR) Europe organization and the project partners. The target respondents for this survey were mainly senior managers or middle managers with direct responsibility for environmental issues. In case that there is no devoted person in the organization for environmental management, target respondents were senior managers or middle managers with direct responsibility for supply chain management or logistics. Each company was asked to respond once to the questionnaire.

The questionnaire was available both online and in a pdf/word format. To collect the required data, we contacted by a phone call each one of the twenty two ECR Local initiatives and we asked them to distribute a survey invitation to their members. Due to the fact that most of the ECR Local Initiatives had already run various surveys in the previous period and some of them did not have Sustainability issues in their agenda, only 8 out of 22 ECR local Initiatives decided to support the survey. They distributed the questionnaire either to their local members or to specific members that work on environmental sustainability issues These were: ECR Italy, GS1 Portugal, GS1/ECR Hungary, ECR Polska, GS1 Netherland, ECR Hellas, GS1 Sweden, IGD/ECR UK. The email invitation was finally sent to 238 members by the above ECR Local Initiatives. In Greece, where an industry group worked on environmental issues, firms engagement was higher and, as a result, the response rate in Greece is almost 50%. In the rest of the European countries, the response rate was 12%. Moreover, each of the partners distributed the survey invitation to selected partners. To encourage participation, it was mentioned that the results of the survey would be provided to each participant at the end of survey. The survey was carried out from March 2012 to June 2012. In case there was no response after three weeks, the contact person was contacted again by email. If there was still no response, phone calls were made in some cases.

To analyze the questionnaire data, examine the research model and test the hypotheses, a variety of analytic techniques and tools was used. SPSS software was used to organize the data and run preliminary descriptive analyses.

The sample consists of 79 different companies. Suppliers, manufactures, retailers and 3PL took part at the survey. The majority of respondents (73 %) are suppliers and manufacturers and most of them came from Greece. However, they represent mainly either headquarters of a multinational company or the local organization of a multinational company, thus we can generalize in some degree the results and conclusions that came out. Moreover, the questionnaire was completed mainly by environmental managers or supply chain managers. In order to complete the questionnaire in an accurate way, in 20 % of the firms a team of employees/managers that represent different departments participated in answering the questionnaire. 92 % of the respondents belong to high, senior and middle management of a firm.

2.2.4 Application of an Energy and Carbon Measurement Scenario

Last decades, energy and carbon management in the supply chain has raised a growing interest and various efforts to measure the energy and carbon emissions have taken place. However, a widely accepted and applied methodology for energy consumption and carbon footprint measurement, that would ensure the comparability of the various estimations, is still missing. According to the Green House Gases Protocol (WRI, 2012), CO_2 emissions are measured in tonnes of carbon dioxide equivalent (CO_2e). The above metric has been accepted as the global warming measure of warming (Global Warming Potential) and summarizes the following six gases associated with the greenhouse effect: NOx, SF6, CH4, N2O, HFCs and PFCs. The applied methodologies focus mainly on measuring total emissions for a specified period by using aggregated data and do not consider the allocation of energy consumption and carbon emissions to different levels of analysis.

For measuring energy and CO_2e, several standards have been developed. One widely adopted is the gas (GHG) protocol (WRI, 2012). The GHG protocol categorized three scopes of GHG emissions (scope 1, scope 2, and scope 3), which have become widely accepted and utilized in a number of regulations and standards. Another reporting standard is EU ETS (EC, 2008). Other pertinent reporting standards include the Global Reporting Initiative (GRI) Guidelines (GRI, 2011), the International Organization for Standardization (ISO) 14064 (Wintergreen & Delaney, 2007), ISO 50001 (ISO, 2011) and Publicly Available Specification (PAS) 2050 (BSI, 2011). Moreover, in the context of supply chain, The 2016 KPI Team has developed a comprehensive and practical set of KPIs for CO_2 emission and energy consumption reduction, ready for use by consumer goods companies. There are also linked measures for transportation and warehousing activities in different parts of the supply chain (The Consumer Good Forum, 2012). Based on the applied methodology, we may have differentiations at the estimations. Moreover, the final estimations may vary significantly depending on the accuracy of the available data.

Within this working group, the focus has been on investigating the different levels of data accuracy and how this guides the selection of different energy and carbon emissions calculation methods. As the reduction of total emissions at product level is recognized as important, special emphasis was put on developing a calculation approach for estimating energy consumption and carbon emissions at the product level. So, alternative approaches for calculating the total equivalent carbon dioxide emissions were developed as well as three alternative approaches for calculating the environmental footprint of a product level.

The approach presented below complies with the following standards: the Green House Gases Protocol (WRI, 2012), the European standard for calculating the environmental footprint of transport services as indicated by the European Committee for Standardization (CEN, 2011), the approach of DEFRA and the Working Party 2016 KPI-Team as part of the work "The Consumer Goods Forum" (The Consumer Good Forum, 2012). In detail, the proposed approach presented in ECR Hellas Guide on Calculating Carbon Footprint in the Supply Chain (ECR, 2013)

As the aim of this effort has been to investigate the energy and carbon measurement in a limited supply chain scope but in depth, the approach presented is referred to the distribution phase of the fast moving consumer goods supply chain. The emissions that are taken into account are those arising directly by the fuel consumption during transportation processes either when own fleet or contractors for transport (3rd party logistics) are used.

For the sake of simplicity, the phase of production and storage of products are excluded from this approach. However, these should be included in the assessment of the energy consumption and carbon emissions in the whole supply chain.

In order to implement and benchmark the proposed approaches, we used actual data of the firms participating in this working group. The data refers to the scope of distribution specified above.

The aim of this section is not to emphasize the description of the suggested approaches but on discussing the potential issues and implementation difficulties encountered in the actual application of these approaches. Moreover, the impact that the knowledge of such information might have in making other types of decisions is discussed. Therefore, we focus on the practical application of the suggested approaches by initially presenting the application area and scope and the data used.

This study focuses on the distribution scope extended from the supplier's factory warehouse to the retailer's stores. The distribution is limited within the Greek territory and the storage of products is out of this study scope.

The suggested approaches, as mentioned above, take into account the different levels of detail and data accuracy used in the calculations. The CO_2e emissions that are taken into account come from fuel consumption. Therefore, we firstly need to either know or calculate the overall fuel consumption in order to calculate the respective emissions. We can distinguish three different data categories that are required in order to estimate the fuel consumption and that affect the accuracy of emissions calculation:

- Actual fuel consumption data
- Actual vehicle (e.g. vehicle type, vehicle size) and distance traversed data
- Actual distance traversed data.

The above data should be recorded per route. Route is defined as the distance traversed by a specific vehicle type from the loading point to the delivery point. Based on the above categories, we identify three different approaches for estimating the fuel consumption and respectively three different levels of calculation accuracy, as shown in the following table.

Table 2.2 Data Accuracy for Calculating CO_2e per route

1. Actual fuel consumption data
2. Average CO_2e / Km referring to specific vehicle * distance travelled
3. Average CO_2e / Km referring to specific type and size of vehicle* distance travelled
4. Average CO_2e / Km referring to specific type of vehicle * distance travelled
5. Average CO_2e / Km * distance travelled

In summary, the following information is needed for the carbon emissions calculation:

- Distance traveled per product / delivery
- Fuel consumption - fuel types
- Vehicle type
- Load weight
- Vehicle emission factor per vehicle type

For the applying the specific methodology, we used data given by a member of the working group, more specifically a supplier in the Fast Moving Consumers Good Industry. The data referred to the period July - August 2012 and covered the following scopes of the supply chain:

- Supplier Plant Warehouse – Supplier Warehouse
- Supplier Warehouse – Retailer Stores
- Supplier Warehouse –Retailer Central warehouse

In our case the available data were:

- Distances traversed
- Fuel consumption estimations
- Number of cartons per route and per product
- Truck type
- Truck capacity
- Load weight
- Load volume

By taking into account the fuel consumption data availability, we chose the third way of calculation. Despite the limited scope of energy and carbon measurement scenario, a large amount of data that are kept in different systems is required and the retrieval process, due to absence of automation and integration, is a difficult one. It also highlights the heterogeneity of the data availability levels, which affects the calculation approach selection and consequently makes the results comparability doubtful. Last but not least, it underlines the difficulties of applying this approach at product-level and more specifically across a product life-cycle where the collaboration of various partners is needed and the synchronization of data from different resources is required.

However, despite the limited scope of application, the practitioners recognized and agreed on the importance of measuring the energy and carbon emissions in the supply chain. They state that they could take more informed and environmental-aware decisions regarding distribution processes. Moreover, they underline the fact that actions that focus on reducing energy consumption and carbon emissions could also bring cost reductions and improvements in other supply chain KPIs e.g. vehicle fill rate.

2.2.5 Industry Insights, Open Issues and Research Motivation

In the following section, we summarize the main findings of the ECR project based on the outcomes of the industry survey and the discussions with industry experts. The main findings that we present in this section reveal the industry gaps and consist the motivation of this research.

Finding 1:

Many firms have recognized the importance of environmental issues but they have yet not incorporated them into their strategies. Hence, the industry survey identifies a discrepancy on firms “environmental maturity levels”. On the one hand, there are firms mature enough to expand their environmental practices and adopt systems and services that enable energy and carbon management systems. On the other hand, based on the insight of the data collection process, there are many firms where environment is not a priority and it seems that there is still a lot of awareness training to do for them.

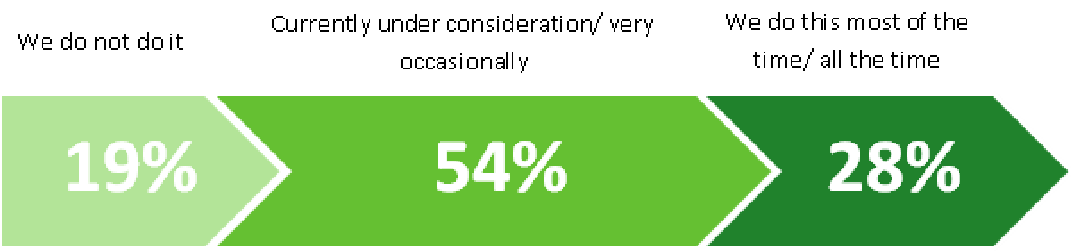

Figure 2.1: To what extent have you deployed a series of environmental practices?

The industry experts support the aforementioned findings and highlight the importance of energy and carbon management in the supply chain. Despite the fact that they underline the need for engaging in energy and carbon management efforts in the supply chain, they stress the fact that there is limited evidence on both the implementation challenges of energy and carbon management and the expected benefits.

Finding 2:

The collaboration enables retailers and suppliers to implement their environmental performance objectives. The industry survey reveals that the degree of collaboration is rather retained which implies that there is still opportunity and potential to leverage further benefits from supply chain collaboration.

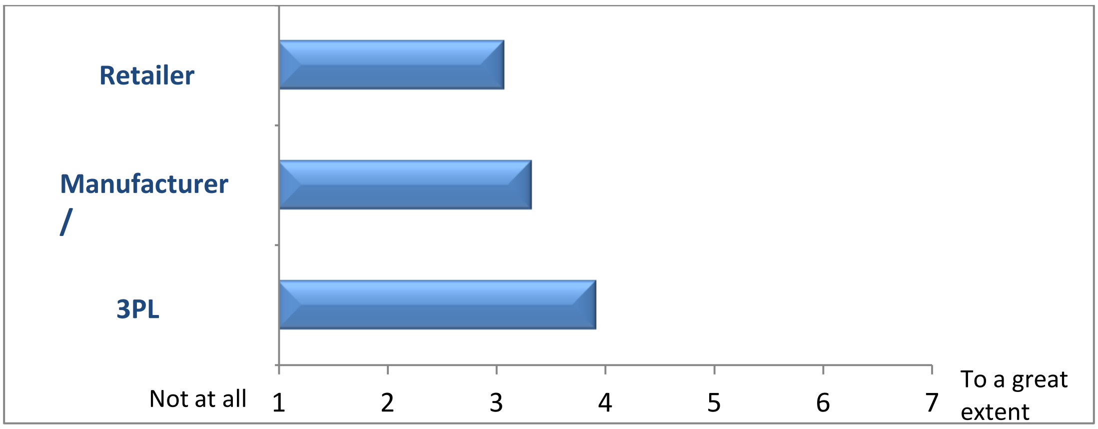

Figure 2.2: Do you collaborate with your supply chain partners?

Industry experts identified the environmental challenges and collaboration on these issues as a vehicle in order to expand the supply chain collaboration, and address simultaneously economic, environmental and supply chain related problems.

Finding 3:

It turned out that shipment consolidation could be considered as the prevalent environmental practice and as a common goal of retailers and suppliers. Both retailers and suppliers are planning to increase vehicle fill rate and develop collaborative distribution solutions. However, the implementation of systems for reporting and measuring energy and carbon emissions is included on the list with the most deployed environmental practices.

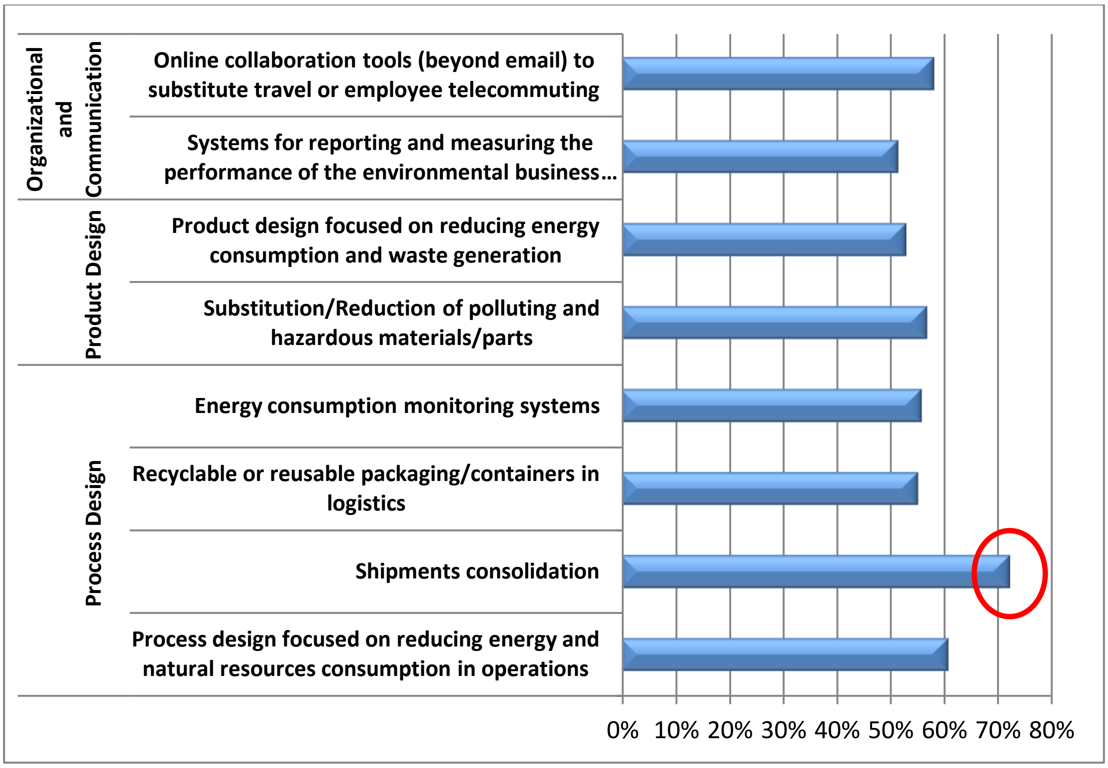

Figure 2.3: Most deployed environmental practices[1]

Based on experts' experience, the current situation in the industry is that companies measure and report energy consumption and carbon emissions on an aggregated basis (monthly or yearly) either referring to the whole organization, to specific organizational units or operations. Measuring energy consumption and GHG emissions across the supply chain is still in its infancy, as it requires a unified approach to measure energy consumption and GHG emissions across the supply chain and the information approaches and rely on information sharing among supply chain partners (retailers, suppliers, transport operators etc.).

Both collaborative environmental practices and energy and carbon management across supply chain demands the collaboration and information sharing but this has not started materializing yet, nor are there information sharing standards currently in place. Therefore, industry experts highlight the fact that the absence of an infrastructure and information sharing mechanisms is one of the main obstacles in the deployment of both collaborative environmental practices and energy and carbon management. Thus, the need of an information system that supports the collaboration and information sharing on environmental issues is more demanding than ever before.

Finding 4:

Suppliers and retailers have implemented various approaches for measuring energy consumption and carbon emissions. However, most of them are not supported by an information system and nowadays many firms are interested in using an energy and carbon management system.

[1] This percentage represents these firms that answer that they do each practice either most of the time or all of the time

[2] 1 = Environmental Corporate Strategy, 2 = Environmental Marketing Strategy, 3 = Environmental

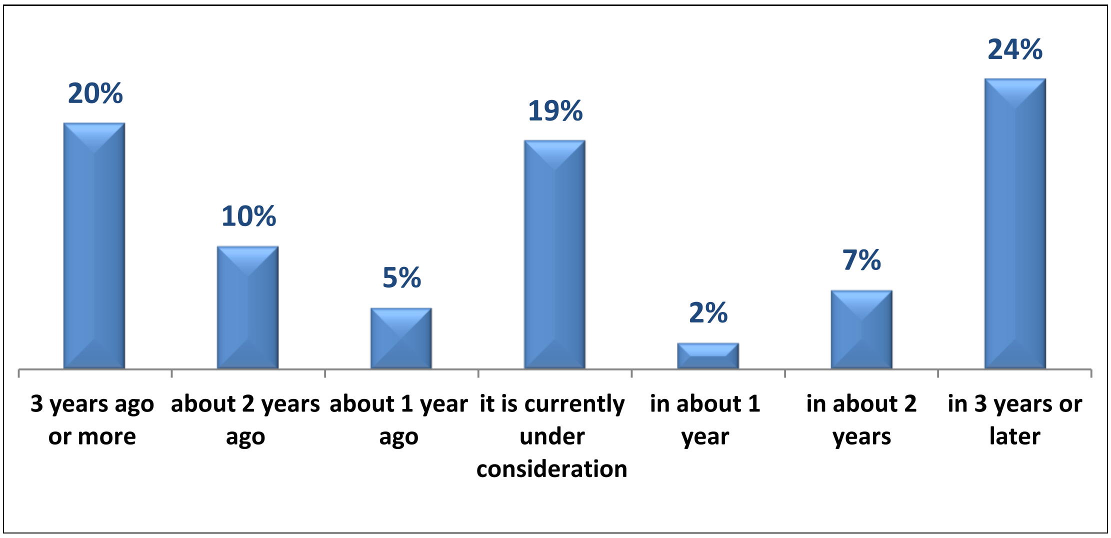

Figure 2.4: When did you employ or plan to employ a software package for energy and carbon management?

In respect to the above, industry experts claims that an energy and carbon management system comes to address the gap of supporting information sharing among supply chain partners to support energy consumption and carbon emissions both internally within a company and across the supply chain. In addition, this system will do so not just at a high aggregated level (company or unit), but down to warehouse/store sections, vehicle and product level, taking into account energy consumption and carbon emissions of warehousing and multi-modal transport. Despite this fact, there appears to be a clear gap currently in the industry and all industry experts have supported this, various related issues such as the exact functionalities or the implementation difficulties should be investigated in more detail.

Finding 5:

Suppliers and retailers have implemented various approaches for measuring energy consumption and carbon emissions at various levels of product life cycle. However, this measurement is limited to specific product life-cycle phases, e.g. manufacturers and suppliers cannot monitor the environmental impact of their products at the point of sales. Thus, collaboration with supply chain partners on energy and carbon management is essential for addressing environmental goals and most of the firms currently considered it. Moreover, information sharing is a prerequisite in order to measure the environmental impacts of products across the supply chain. However, most of the firms are willing and plan to exchange this kind of information in an electronic way in the near future.

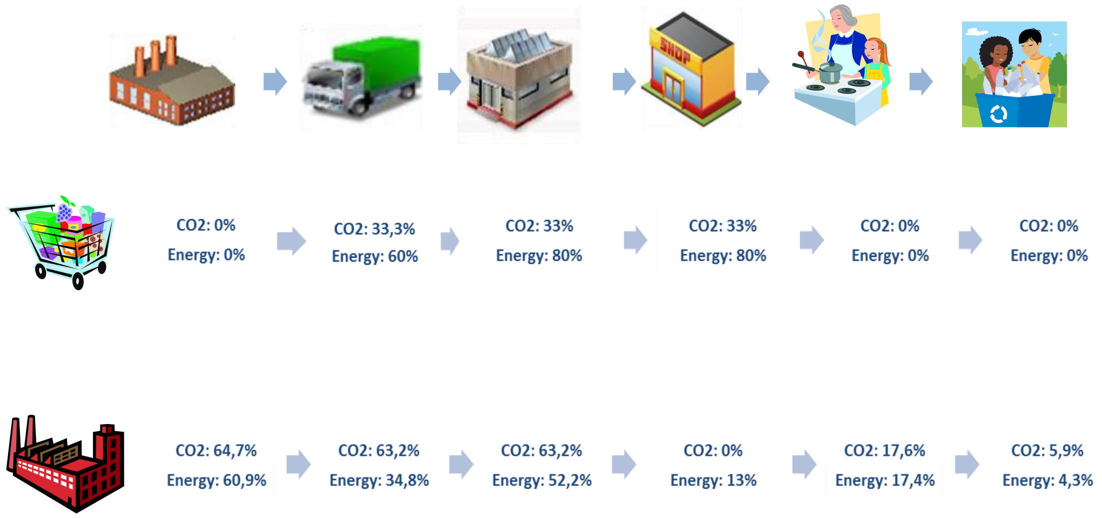

Figure 2.5: To what extent does your firm measure energy consumption/carbon emissions at the various product life-cycle phases?

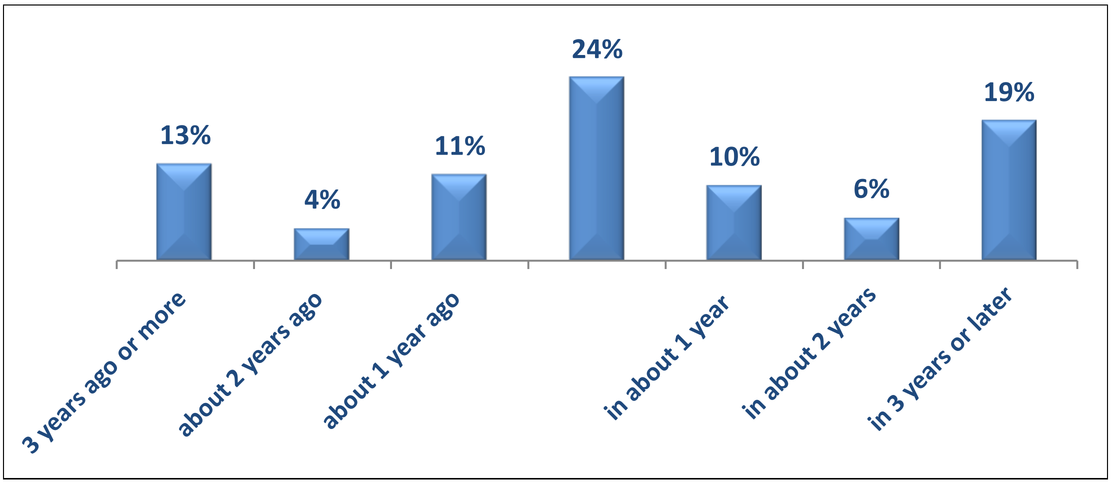

Figure 2.6: When did you employ or plan to employ collaborating programs with your supply chain partners (major customers or primary suppliers) to measure the energy consumption and carbon emissions of products?

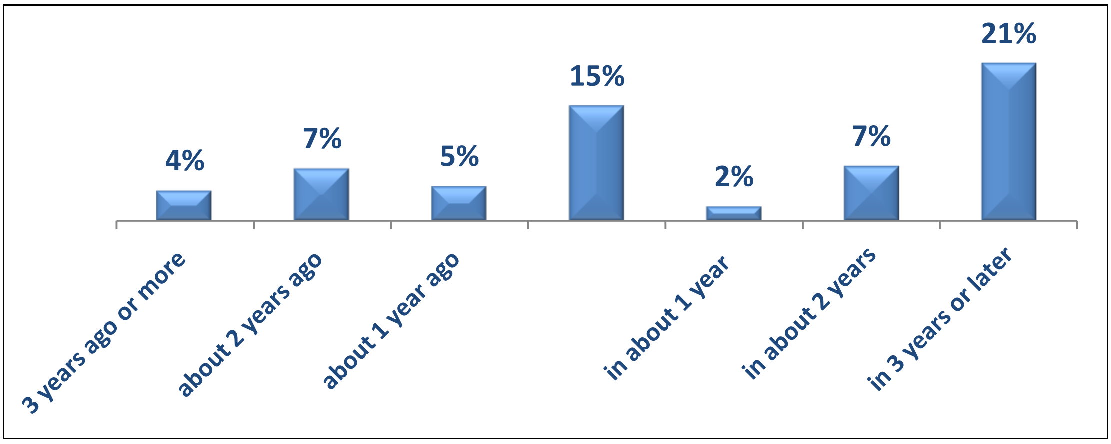

Figure 2.7: When did you employ or plan to employ sharing information electronically with your primary supply chain partners in order to measure the energy consumption and carbon emissions of products?

Industry experts underline the need of expanding energy and carbon management out of the interfirm scope. One more issue that has been identified is the need of a unified measurement approach. There are some common approaches but each company is following its own approach internally. More consensus has currently been achieved in respect to the transportation of goods, where a common methodology for calculation and declaration of energy consumption and GHG emissions of transport services has recently been published (CEN, 2011) and industry initiatives are currently set up to support benchmarking services for road freight (e.g. Green Freight Europe). Along the same lines, a respective working group of the Consumer Goods Forum has also recently (March, 2012) published an approach to measure energy consumption and GHG emissions across the supply chain, covering not just transportation but also warehousing (The Consumers Good Forum, 2012)

Finding 6:

Energy and Carbon Management is a data intensive process and it requires various kinds of data from pure environmental ones to traditional operational ones. Suppliers and retailers keep various kind of data either based on estimations or on measurements with actual data. However, the lack of automation on reporting these data seems to be the current state.

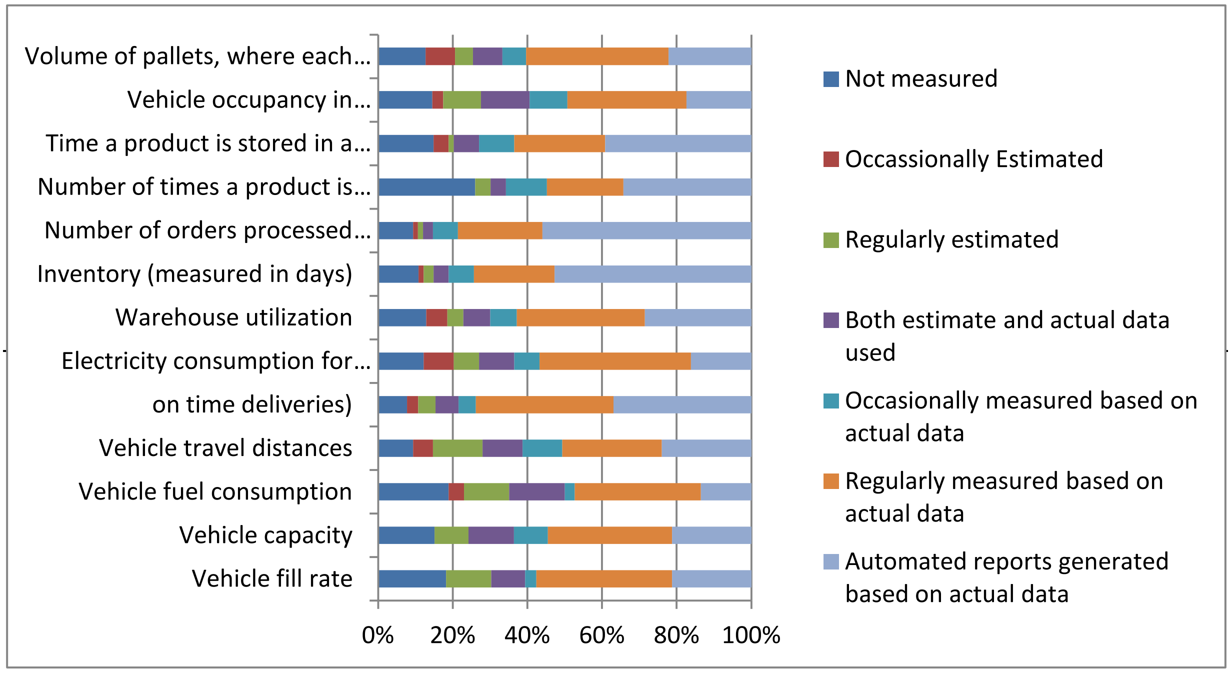

Figure 2.8: To what extent does your firm measure and report the following indices related to energy and carbon management?

The need of automation on the data retrieval processes that will support energy and carbon management is also one of the main findings of the application of an energy and carbon management scenario presented in Section 2.2.4. Despite the limited application scale of the energy and carbon measurements, a series of aspects that should be taken into account at the energy and carbon management raised. These aspects are summarized below:

- **Data quality and availability:** The industry experts claimed that the energy and carbon management is a data intensive process and the data requirements cannot easily be covered by the existing infrastructures. Moreover, even when data are available, they may not cover the level of detail that is required in order to enable energy and carbon management.

- **Data capture and integration:** The industry experts have identified the difficulties of selecting the various types of data and have highlighted the diversities in the systems that could provide them.
- **Environmental Performance Metrics:** Selecting the appropriate environmental performance metrics was one of the main challenges that came up. The metrics should mainly ensure the comparability of the results which seems to be even more difficult in the context of the supply chain as there is no a holistic approach on environmental performance measurement.
- **Collaboration and Information Sharing**: Expanding environmental performance measurement out of the narrow scope of firms imposes the need of addressing issues related to collaboration and information sharing.

<u>Finding 7:</u>

More informed and enhanced with environmental aspects decision-making is the main perceived impact of applying energy and carbon management. Practitioners identified that the lack of environmental information is one of the main obstacles towards the development of sustainable supply chains and the implementation of sustainable supply chain practices. Therefore, they recognized the need of collecting more-detailed environmental information, integrating it in the supply chain processes and presenting it together with traditional supply chain information. For example, they identify the importance of this kind of information for optimizing the distribution processes and inventory management. Moreover, they underline the fact that that actions that focus on improving environmental performance could also bring cost reductions and improvements in other supply chain KPIs e.g. vehicle fill rate. However, empirical findings that prove the impact of selecting environmental information and integrating it on the supply chain decision-making process is required.

2.3 Literature Review

2.3.1 Environmental Performance Measurement

Firms in several industries nowadays implement various practices in order to develop more sustainable supply chains, under the pressure of stricter regulatory requirements, energy costs’ inflation, increasing requests of supply chain partners and mounting environmental awareness of consumers. Measuring and monitoring environmental impacts at the different stages of a supply chain has been recognized as a main issue in the development of sustainable supply chains (Seuring & Müller, 2008). Such a measuring forms the basis for controlling the environmental performance of supply chain processes, for making environmental-aware decisions regarding improvement measures, for tracking the progress in environmental performance identifying potential problems (e.g., bottlenecks), and providing insight into possible future actions (Holmberg, 2000; Gunasekaran et al., 2004; Gunasekaran & Kobu, 2007). Thus, a growing number of firms deploy and monitor various environmental indicators (Olugu et al., 2011; Veleva et al., 2003) and even integrate carbon footprint monitoring in the management of their supply chain (Lee, 2011; Sundarakani, 2010). Given the many players in a supply chain (e.g., suppliers, focal firm, distributors, retailers, customers, etc.), environmental performance measurement is a challenging issue (Ahi & Searcy, 2013) and its level of implementation still remains low.

In that end, there is a rapidly growing body of literature that focuses on the environmental performance measurement and, more specifically, on addressing the question of how to measure supply chain wide sustainability performance (Bjorklund et al., 2012; Tattichi et al., 2013). Bjorklund et al. (2012) frames environmental measurement in supply chain management by suggesting a series of dimensions that should be used for the successful application of environmental performance measurements. An analytical framework for the assessment of approaches for the measurement and management in light of measurement and management supply chain strategies and SPSC goals is proposed by Schaltegger & Burritt (2014). They underline the importance of measuring specific information about opportunities and risks in order to support not only improvement and efficiency purposes but also decision-making and strategies for SSCM. Moreover, Tattichi et al. (2013) has conducted a literature review in the field of sustainable supply chain performance measurement (SSCPM) and proposes a research agenda highlighting the importance of defining SSCPM frameworks and the need for more empirical evidence on these issues. As a final illustrative example, it is interesting to refer the recent special issue on performance measurement of sustainable supply chains in the International Journal of Productivity and Performance Measurement (e.g., Pazirandeh & Jafari, 2013; Reefke & Trocchi, 2013; Taticchi et al., 2013; Wang and Sarkis, 2013)

The identification of the performance metrics is a critical aspect of the environmental performance measurement. In that end, the literature proliferates of studies on environmental performance measurement focusing on metrics (Bai et al., 2012; Bai & Sarkis, 2014; Chae, 2009). Hassini et al., 2012 towards an extensive literature review identifies a list of more than one hundred indicators that can be used and provide a list of frameworks for SSC management and environmental performance measurement. Searcy et al. (2007) present a case study of sustainable performance indicators for an electric utility company. Sarkis et al. (2010) provide guidelines and an extensive list of metrics for measuring the social sustainability of reverse logistics practices. Olugu et al. (2011) develops an integrated Performance Measurement system for measuring the environmental sustainability of supply chains in the automobile industry. Bai et al. (2012) propose a methodology for identifying and selecting measuring environmental sustainable supply chain key performance indicators (KPI) for suppliers evaluation based on Grey system theory and the Supply Chain Operations Reference model (SCOR). As another illustrative example, we note the Ahi & Searcy (2014) extended literature review on metrics used to measure performance in green and sustainable supply chains and proposed a framework for measuring environmental performance by taking into account. Their framework ensures that SSCM metrics address the key players in the supply chain, address the broader sustainability context of the supply chain and the key characteristics of GSCM and SSCM as suggested by Ahi & Searcy (2013). Moreover, Ahi & Searcy (2014) review identified a total of 2555 unique metrics.

Although there is no shortage of environmental indicators, there is a difficulty in deciding on which ones to use, when and how. A first approach for discovering how the complexity of metrics could be reduced is by selecting and aligning them with different strategies and actions or even decisions. For example, Bai & Sarkis (2014) proposed an approach for selecting a set of metrics in the face of addressing different impacts and aspects. Ahi & Searcy (2014) found that only five metrics were often used: quality, air emissions, greenhouse gas emissions, energy use, and energy consumption. Therefore, environmental performance measurement could be focused on specific type of indicators in order to reduce complexity. As energy consumption and carbon emission are the most prevalent metrics, energy management focusing on energy consumption (Bunse et al., 2011) and carbon accounting (Schaltegger & Csutora, 2012) focusing on greenhouse gas emissions could be considered as discrete and two of the most prevalent categories of environmental performance measurement.

Even though previous studies promote measuring environmental performance in supply chains (e.g. Veleva et al. 2003; Hervani et al., 2005; Markley & Davis, 2007), measuring the environmental performance of supply chains remains non-trivial due to several reasons. These include: limited data availability (Bjorklund et al., 2012; Veleva et al., 2003); different supply chain players have to agree on which metrics to use and with which data (Hervani et al., 2005); incompatibility between classical production measures, which are designed for intra-organizational management and supply chain measures that should have an inter-organizational scope(Lehtinen & Ahola, 2010); lack of an oversight agency that controls the whole supply chain (Hassini et al., 2012); lack of trust in the relationship and fear that data confidentiality may be compromised (Hassini et al., 2012); and insufficient capturing of non-traditional performance data by current enterprise systems (Hervani et al., 2005). Still, incorporating both environmental and non-environmental aspects is crucial for tackling the trade-offs among the distinct performance aspects (Björklund et al., 2012; Caplice & Sheffi, 1995; Keating et al., 2008; McIntyre et al., 1998, Shaw et al., 2010; Vanteddu et al., 2006)

Thus, in this context, information systems can support firms to confront the main issues discussed above by enabling them to standardize, monitor, capture, and utilize data and metadata (Björklund et al., 2012; Dao et al., 2011; Hervani et al., 2005; Melville, 2010). In the realms of supply chain, they could also facilitate both collaboration and information exchange by improving information flows among supply chain partners (Banker et al., 2006). Moreover, they could support operational and strategic decisions and also optimize processes by taking into account not only traditional key performance indicators (KPIs), such as cost and service level, but also environmental KPIs and the dynamic energy profile of products and processes (Bunse et al., 2011; Watson et al., 2010). Last but not least, they could also incorporate life cycle analysis methodologies and capture and process the required data in order to support the measurements of impacts at product level (Shaft et al., 2008; Melville, 2010).

Mindful of this potential, a new class of information systems emerges, the Energy and Carbon Management Systems (ECMS) (Melville & Whisnant, 2014). ECMS is a type of enterprise information system that "takes as inputs various types of environmental data (e.g., electricity and fuel use, furnace combustion, emission factors, employee commuting, and air travel), processes that data into usable information, (e.g., megajoules of energy, GHG emissions), and provides enhanced functionality (e.g., automated reporting, managerial dashboards, supply-chain analytics, and workflow management)" (Melville & Whisnant, 2014). More specifically, these systems are required to capture energy and carbon related information from energy consumption measurement infrastructures, to collect and analyze operational data sets from a company's existing enterprise systems (e.g., ERP) or even its supply chain partners enterprise systems and then to integrate environmental with other information flows in order to calculate and monitor both the environmental and traditional performance indicators of processes and products.

To sum up, past efforts indicate the significance of the environmental performance measurement in the supply chain management. Due to the need of reducing its implementation complexities, environmental performance measurement could focus on energy and carbon indicators. In that end, energy and carbon management has been recognized as a significant sub-category of environmental performance measurement and issues related to its implementation have been discussed. However, there is not adequate empirical evidence on which is the purpose and scope of energy and carbon management in the supply chain expressed e.g. in business needs, key performance indicators and data requirements. In this context, Information systems (IS) recognized to be an enabler of energy and carbon management by acting as a tool for monitoring energy and carbon emissions in the supply chain and thus pinpointing areas for improvement and savings. These systems, *called as Energy and Carbon Management Systems (ECMS) could also be the basis for supporting the development of more sustainable supply chain processes and products. However, there is no adequate research that shows how the ECMS serves Energy and Carbon Management requirements and how a system could address the identified implementation issues.*

2.3.2 Green Information Systems

The current sustainability challenges have motivated research in various disciplines for decades. As discussed in previous sections, business researchers have investigated the notion of sustainability in the supply chain management (e.g. Fahimnia et al., 2015; Seuring & Muller, 2008; Srivastava, 2007), in management and (e.g. Etzion, 2007), in economics (e.g. Lyon & Maxwell, 2007) and in marketing (e.g. Chabowski et al., 2010; Connelly et al., 2010). However, limited research has been conducted that incorporates the information systems perspective. Only but recently, "Green IS" was introduced as a new research era in the information systems discipline (Watson et al., 2008).

Watson et al. (2008) distinguished the notion of Green IT and Green IS by claiming that information technology transmits, processes, or stores information while information system (IS) is an integrated and cooperating set of software using information technologies to support individual, group, organizational, or societal goals. Based on the above, Green IS refers to the design and implementation of information systems that contribute to sustainable business processes". Green IS, for example, helps an organization to reduce transportation costs with a fleet management system and dynamic routing of vehicles to avoid traffic congestion and minimize energy consumption, to support team work and meetings when employees are distributed throughout the world, and thus reduce the impact of air travel, to track environmental information (such as toxicity, energy used, water used, etc.) about the creation of products, their components, and the fulfilment of services or to monitor a firm's operational emissions and waste products to manage them more effectively. Various definitions of Green IS are met in the various studies as the Green IS field is an emerging research field. According to Elliot (2011), Green IS is defined as "activities to minimize the negative impacts and maximize the positive impacts of human behavior on the environment through the design, production, application, operation, and disposal of IT and IT-enabled products and services throughout their life cycle". Moreover, Loeser (2013) provide substantial reviews of the terms Green IS, Green IT, and IT for environmental sustainability and their specific meanings.

Previous studies in the IS literature have discussed the role of information systems in addressing sustainability goals in general (Elliot, 2011; Jenkin et al., 2011; Melville, 2010; Watson et al., 2010) and motivate further research in the field. Elliot (2011), Jenkin et al. (2011), Melville (2010) and Malhotra et al. (2013) provide substantial reviews in the green information systems literature by drawing broadly from research that addresses environmental sustainability in the management, environmental psychology, social marketing, and environmental management and information systems domains. Building on recent reviews, Malhotra et al. (2013) have identified only 14 articles total within the AIS basket of the eight leading IS journals and 9 articles in eight environmental management journals for the six-year span of 2008–2013. In their review, they underline the need of research on the design and the impact of Green IS. Moreover, the majority of the current Green IS studies have been published in the most prominent IS conferences which impose the nascent nature of the Green IS research.

Moreover, Melville (2010) grounded a Belief-Action-Outcome Framework by taking into account the three main classes of sustainability phenomena that the review process revealed: (a) the emerging cognitive states about sustainability, (b) the actions of organizations and individuals regarding sustainability practices and processes; and (c) the environmental and financial impacts. Their proposed framework highlights the role that IS can play in shaping beliefs about the environment, in enabling and transforming sustainable processes and practices in organizations, and in improving environmental and economic performance and framed the respective research issues. Special emphasis has been given on identifying the association between information systems and supply chain performance from an efficiency and environmental perspective and on defining the design approaches that are effective for developing information systems that support sustainability objectives.

Elliot (2011) conducted a detailed review in order to define the meaning of environmental sustainability, its major challenges and the actions that have been already taken on this direction and the future requirements and needs and developed a holistic, transdisciplinary, integrative framework for IT-enabled business transformation. Jenkin et al. (2011) proposed a framework with four pillars, environmental sustainability motivating forces, and environmental sustainability initiatives: strategies and technologies/systems, overall environmental orientation and environmental impacts. Based on these aspects, they identify the important research gaps and suggest a set of propositions. Besides, the studies that are published in the JSIS and MISQ special issues on Green IS are noteworthy. In the JSIS special issue on Green IS (Berthon & Donnellan, 2011), eight studies have been published that study Green IS from a decision-making perspective and focus on four key dimensions: regulations that firms increasingly have to comply with (Butler, 2011), new technologies that try to address sustainability issues (Pitt et al., 2011), the assessment of the environmental practices e.g. protocols and technologies that a firm should adopt (Bose & Luo, 2011; Dao et al., 2011; Watson et al., 2011; Zhang et al., 2011) and measuring the consequences of any adoption (Bengtsson & Ågerfalk, 2011; DesAutels & Berthon, 2011). In the MISQ special issue (Malhotra et al., 2013), three paper are published that focus on transformation themes and more specifically on the role of Green IS on organizational transformations, supply-side transformations and consumption-side transformations. Due to the nascent nature of the Green IS area, most of the studies are conceptual and propose general frameworks for framing research in the Green IS field.

However, there are a few empirical analyses that focus and explore specific types of systems and issues related to these systems including, for example performance evaluation and environmental reporting (Figge et al., 2002) and knowledge management systems for environmental sustainability goals (Jain et al., 2008; Jenkin et al., 2011; Manning, 2007). As we can see in previous studies, there are various types of systems that could be characterized as Green IS. However, Green IS field still lacks an exact specification of the scope of Green IS era and a classification of the systems that could be characterized as Green IS. In order to cover this gap, SIGGREEN AIS working group has made a preliminary effort to frame the research on Green IS field and to specify a taxonomy of GREEN IS research and Green IS, which includes various categories e.g.: creating, managing and using information, decision support for environmentally sustainable development, changing attitudes and behavior, the Greening of IT. As the taxonomy is still a “work in progress”, the various categories have not yet clearly specified.

However, another interesting classification identifies two broad categories of systems by taking into account the information value chain (El-Gayar & Fritz, 2006): the Environmental Management Information Systems that are "concerned with the efficient collection of performance data to directly support performance measurement and process improvement" and the Environmental Decision Supports Systems that "facilitate strategies of business process re-engineering, and technological innovation. It supports strategies of process improvement and work flow optimization."

Indicative examples of EMIS could be the following: performance evaluation and environmental reporting systems (Figge et al., 2002), measurement and accounting systems (Brown et al., 2005; Goodman, 2000; Heng & de Moor, 2003; Isenmann et al., 2007; Moller & Schaltegger, 2005; Rikhardsson, 1998; Shaft et al., 2001), performance evaluation and environmental reporting systems (Figge et al., 2002), measurement and accounting systems (Brown et al., 2005; Goodman, 2000; Heng & de Moor, 2003; Isenmann et al., 2007; Moller & Schaltegger, 2005; Rikhardsson, 1998; Shaft et al., 2001), environmental resource planning (ERP) systems (Melville, 2012; Melville & Saldanha, 2013) and energy and carbon management systems (Melville & Whisnant,, 2014). Indicative examples of Environmental Decision Supports Systems could be the following: supply chain systems that support vehicle routing optimization and minimization of energy consumed during transportation, information systems for managing environmental compliance issues (Butler 2011), business intelligent systems (Petrini & Pozzebon, 2009) or the environmentally conscious design of information systems (Zhang et al. 2011). Summarizing, these aforementioned systems expected to support environmental management but also support sense-making, enable and enhance decision-making and knowledge creation in terms of environmental impacts within organizations (Butler, 2011; vom Brocke & Seidel, 2012, Seidel et al., 2013; Shrouf & Miragliotta, 2015).

Moreover, Melville (2010) highlights the need of rigorous research in order to determine to what extent IS might improve sustainability in the realm of supply chains. Transportation and logistics have been transformed by previous information technologies such as radio-frequency identification (RFID) enhancing the effectiveness of firms via information-based capabilities (Kohli & Melville, 2009).

Therefore, the impact that these systems may have on enabling and enhancing sense-making and environmental-aware decision making is still underexplored.

To sum up, there is only limited research on the actual design of such systems or their implementation in a real-world context (Malhotra et al., 2013; Seidel et al., 2013) and especially in the supply chain context. While a lot of focus has been on conceptualization, e.g. review papers, conceptual frameworks (Butler, 2011; Dao et al., 2011) or analysis, e.g. case studies, quantitative empirical analysis (Bengtsson & Agerfalk, 2011; Benitez-Amado & Walczuch, 2012; Bolívar, 2009), a design science approach is further needed to specify the functionalities that could be integrated in these systems or the information that must be transmitted, processed, and stored (Malhotra et al., 2013; Seidel et al., 2013). Going a step further, researchers must not only work on the actual design of these systems but also establish the "in-field" impact of such systems in order to shed light on the implementation process and any related underlying phenomena (Malhotra et al., 2013). Moreover, further research is required in order to investigate how these systems impact the implementation of environmentally sustainable supply chains by supporting energy and carbon management, environmental-aware decision-making and the implementation of environmentally sustainable supply chain practices.

2.3.3 Environmental Management Information Systems

Previous research studies have discussed the critical role of information systems in the development of energy and carbon management and have revealed an emerging class of information systems focusing on the energy and carbon management called as Energy and Carbon Management Systems (ECMS) (Melville & Whisnant, 2014). More specifically, these systems should be able to capture energy and carbon related information from energy consumption measurement infrastructures, to integrate and interoperate with a company's existing enterprise systems (e.g., ERP, WMS, MES), to interpret and integrate the data received from various sources, to exchange data with the enterprise systems of supply chain partners and support decision making in the supply chain. ECMS could be considered a sub-category of a broader category of systems known as Environmental Management Information Systems (Teuteberg & Straßenburg, 2009) as it focuses only on managing two types of environmental indicators, the energy consumption and carbon emissions. Therefore, in this section we focus on the broader category of EMIS and present previous related studies. Environmental management information systems (EMIS) are defined as 'organizational-technical systems for systematically obtaining, processing, and making available relevant environmental information available in companies' (Page & Rautenstrauch, 2001)

Environmental management information systems (EMIS) are differentiated into information systems for external reporting, eco-controlling systems for internal operations research, life cycle assessment systems, key performance indicator based systems, environmental accounting systems, sustainability reporting systems, input-oriented systems, output-oriented systems, process-oriented systems and production-related EMIS (Teuteberg & Straßenburg, 2009). However, a clear classification of the EMIS is still missing. El-Gayar & Fritz (2006) identified five clusters of EMIS by taking into account the environmental business goals hierarchy, namely, environmental compliance, pollution prevention, eco-efficiency, product stewardship, and sustainable development, and provided some examples for each category. The goal hierarchy proposes a progressive implementation of EMIS starting from systems such as Legal and Environmental Health & Safety (EHS) databases that ensures regulatory compliance to systems such as Stakeholder focused Multiple Criteria Analysis (MCA) that promotes sustainable development.

Despite the proliferation of EMIS in industry, the relevant studies in the IS area are limited and mainly use the design science' (prototyping) and 'argumentative-deductive research methods. For example, Hilpert et al., (2011) present a cost-efficient system for real-time data gathering for product carbon footprints in transportation processes based on vehicle on-board systems and smart phones Hilpert et al., 2014 propose a mobile application for GHG emission data collection that uses automated sensor systems. A Green IS artifact that is capable to collect process and report energy consumption and GHG emissions on product and process level has been developed in three meat-processing companies (Hilpert et al., 2013). Corbett (2013) discusses how Carbon Management Systems can be designed and used in order to persuade employees to perform ecologically responsible behaviors by using three case studies. Similar efforts have been conducted by Athanasiadis & Mitkas (2004) and Karatzas et al., (2001) that focus on agent-based intelligent environmental monitoring system and Web-based tools for environmental management respectively. However, detailed and tangible functional requirements for EMIS have not been proposed yet (Junker, 2010) and further research is needed.

Focusing on EMIS, we can observe that most of these systems cannot capture actual energy consumption and do not integrate energy and carbon related information with process or operational information (Lee, 2003). Despite the growing interest on EMIS, there are still obstacles that should be overcome and challenges that should be addressed. Melville, (2012) use real cases to identify unique data challenges that arise mainly from the nature of the required data (e.g. heterogeneous data, secondary data, unsystematic, highly distributed, heterogeneous, spatial and time relative). Analogous importance is attributed to the data acquisition and the related data granularity (El-Gayar &Fritz, 2006; Watson et al., 2010; Melville, 2012) and availability (El-Gayar & Fritz, 2006; Erlandsson & Tillman, 2009). Interestingly, data integration is critical (Carlson et al., 2001; Eun et al., 2009; Hilpert et al., 2011) as these systems are usually not integrated with enterprise systems, thus not feeding carbon footprint into relevant decision processes (Liu & Stallaert, 2010). Moreover, Melville

& Whisnant, (2014) towards qualitative interview data from two organizations using ECMS revealed challenges in the areas of business processes, managerial capabilities, data capture and integration, and data quality.

However, further research is needed to show how an EMIS can address these challenges in terms of design e.g. which could be the design principles that an EMIS should follow in order to address the challenges of limited environmental availability. Moreover, Watson et al. (2010) gives emphasis on the integration of the various information flows in the context of Energy Informatics and stress the question of how can an information system integrate various information flows in order to increase energy efficiency. Moreover, previous studies suggest the need for insights into how ECMS operate in practice, how they are implemented, and recommendations for their effective implementation and use (Watson et al., 2010; Melville 2010)."

Except from processing and making environmental information available (Page & Rautenstrauch, 2001), e.g. for environmental accounting and reporting (El-Gayar & Fritz 2006), EMIS have also as objective to enable sense-making, decision-making and knowledge creation in terms of environmental impacts within organizations (vom Brocke & Seidel, 2012). Therefore, another stream of research discusses the role of EMIS on supporting sustainable supply chain practices implementation (Seidel et al., 2013) and enhancing environmental-aware decision-making (Butler., 2011; vom Brocke & Seidel, 2012, Seidel et al., 2013; Shrouf & Miragliotta, 2015).For example, Stindt (2014) designed an EMIS that helps firms to improve decision-making processes in the reverse logistics. Besides, Stindt et al. (2014) discussed how an EMIS could improve the quality of corporate sustainable decision-making by employing a design-science approach, designing an artifact and to develop an EMIS and deploying it within a real-world case study. However, there is still a significant research gap in this area and an imperative need for further empirical evidence.

To sum up, further research is needed for addressing the actual design of such systems or their implementation in a real-world context (Malhotra et al., 2013; Seidel et al., 2013). Previous studies suggest the need for insights into how ECMS operate in practice, how they are implemented, and recommendations for their effective implementation and use (Watson et al. 2010; Melville 2010). Therefore, specifying the design and implementation principles that will guide the design and development of these systems is required. Moreover, the various implementation challenges could be a critical aspect affecting the design of these systems and should be taken into account. Last but not least, further research is needed to evaluate the efficacy and quality of EMIS (El-Gayar & Fritz, 2006), the positive and negative consequences of this systems to the change of work practices (Seidel et al., 2013) or the enhancement of decision making (Loeser, 2013).

2.4 Insights on the Impact of Energy and Carbon Management Systems: Adopting an IT-Business Strategic Alignment perspective

2.4.1 Introduction

During the last decades, environmental issues have come to the forefront and firms have developed and deployed environmentally friendly strategies and practices. Therefore, firms, under the pressure of their stakeholders, have implemented various environmental strategies in order to manage the interface between their business and the natural environment (Aragon-Correa & Sharma, 2003). A firm's environmental strategy may be materialized through various environmental practices, such as product and process innovations for pollution prevention, use of life cycle analysis (Aragón-Correa et al., 2008), acquisition of clean technology/ equipment, shipments consolidation, selection of cleaner transportation methods (Doonan et al., 2005; Shi et al., 2012; Zhu & Sarkis, 2004; Zhu et al., 2005), as well as through the implementation of information systems (Jenkin et al., 2011). The deployment of information systems to cope with environmental challenges is a new area of development and since 2007 only a small number of publications address this topic (e.g., Elliot, 2011; Melville, 2010; Watson et. al., 2010).

At the same time, scholars in the information systems field have long dealt with the fit between IS and business strategies and have argued that information systems can be a key enabler of more efficient implementation of business strategies. However, at present, the role of information systems as an enabler of firm environmental strategies is by far underexplored. The study presented in this section addresses this gap and shed light on the strategic role of information systems from an environmental perspective by exploring the relationship between environmental business strategies, information systems and impact on environmental performance.

Convergent with most research on this topic, this study uses a narrow conceptualization of the strategic alignment of Information Technology (IT), builds on the conceptual foundations of the literature on IT-business strategic alignment and tries to explain how a firm's environmental strategy can be supported by information systems. It illustrates what is currently a realized (as contrasted with planned) environmental IS strategy in alignment with an environmental business strategy and the impact that this relationship has on corporate environmental performance. Specifically, we assume that IS strategy is reflected in the pattern of a firm’s deployment of its IT applications and information systems (Oh & Pinsonneault, 2007; Tallon et al., 2000) and use the term "IS Environmental Strategy" to specifically refer to the deployed IT applications and information systems in alignment with a firm's environmental strategy.

In order to address the above, a research model and a set of hypotheses examining the relationship between environmental business strategy, information systems and environmental performance was formulated (Section 2.4.2). An industry survey was employed as research tool and the research hypotheses are then tested based on data collected by using structural equation modeling analysis and discussed (Section 2.4.3).

2.4.2 Research Model

2.4.2.1 Realized Environmental IS Strategy

The study of the relationships between information systems, environmental business strategies and environmental performance is a cutting-edge research topic in the information systems research domain that is currently underexplored. Some initial efforts have examined the role of IS/IT as a tool to help organizations implement more sustainable business processes (Watson et al., 2010) or as the basis for new ways of delivering products with less energy and carbon emissions (Bunse et al., 2011). Jenkin et al. (2011) first make the link between environmental motives and the development of an environmental IS strategy and proposes a framework to guide future research in the field. Another stream of research examines information systems not as an enabler but rather looks at the environmental implications of IT and IS in organizations (Elliot & Binney, 2008; Haigh & Griffiths, 2008; Sarkis & Zhu, 2008). Closer to the work presented in this study is the research of Benitez-Amado & Walczuch (2012) who have examined how IT capabilities in general can affect firm performance via supporting a proactive corporate environmental strategy. They consider a proactive corporate environmental strategy as a mediator between IT capabilities and firm performance. Contrary to their approach, in this paper we do not consider IT capabilities in general but look at specific IT applications and information systems that support an environmental strategy and consider the impact on firm performance stemming from the IT-business strategic alignment (Chan et al, 1997).

In general, research on IT-business strategic alignment has argued that IT is a key enabler of more efficient implementation of business strategies, while also arguing that it is plausible to fit IT and business strategies to generate business value (Benitez-Amado & Walczuch, 2012). However, there is a lack of literature about the implementation of environmental strategies and few studies have addressed the impact of the environmental factor on the corporate and marketing strategies of industrial firms. Convergent with most research on this topic, in this paper we assume that IT strategy is reflected in the pattern of a firm’s deployment of its IT applications and information systems (Oh & Pinsonneault, 2007; Tallon et al. 2000) and use the term "IS Environmental Strategy" to specifically refer to the deployed IT applications and information systems in alignment with a firm's environmental strategy. IT/IS strategy, as is the case for business strategies, can be understood as either intended (i.e., planned and expected) or realized (i.e., patterns in actions or behaviors) (Mintzberg, 1987; Weick, 1995). In this study, we conceptualize and operationalize strategic alignment of IT based on the realized IT/IS strategy (i.e., the pattern of deployment of IT applications).

Based on a series of workshops and in-depth discussions with industry executives in the fields of sustainability, energy and carbon management in the supply chain, information systems that supports energy and carbon management have been recently deployed, in order to support environmental business strategies. In this context a new class of information systems that support the measurement, recording, monitoring and analysis of environmental impacts (e.g. energy/ fuel consumption, CO_2 emissions, etc.), called as energy and carbon management systems, emerges. We could further identify various types of energy and carbon management systems e.g. Energy Efficiency Monitoring Systems, Life Cycle Assessment Tools, Carbon Emissions Monitoring Systems during Distribution.

The main characteristic of the IT applications and systems described above is that they aim specifically at either monitoring or reducing the environmental impact of a firm's products and/or processes. IT applications and information systems may also have an indirect effect on the carbon emissions of a firm, by enabling e.g. telecommuting and electronic communications (Jenkin et al., 2011) or the adoption of a proactive corporate environmental strategy (Benitez-Amado & Walczuch, 2012). However, we consider that this use of IT/IS is not part of an environmental IS strategy as defined in the scope of this paper. Moreover, due to the fact that energy and carbon management information systems are currently much more deployed compared to information systems affecting environmental impacts as described above, we consider that the realization of an Environmental IS Strategy is mainly expressed nowadays through the implementation and use of environmental monitoring systems. In the following sections, we develop a set of hypotheses to test the impact of an Environmental IS Strategy, as expressed through the use of environmental monitoring systems, on a firm's environmental performance and associate it to a firm's environmental business strategy.

2.4.2.2 The relationship between environmental IS strategy and performance

An extensive body of literature has analyzed the relationship between IT-business strategic alignment and firm performance. Oh & Pinsonneault (2007) make the distinction between the resource-centered perspective and the contingency perspective of the strategic value of IT. The resource-centered perspective either looks at the strategic value of IT as a function between the size of IT investment and organizational performance (Barua et al., 1995; Hitt & Brynjolfsson, 1996) or focus more on the importance of the scope and quality of resources, following the resource-based view (e.g. Barney, 1991; Bharadwaj, 2000; Caldeira & Ward, 2003). The contingency theory, which is the one adopted in this paper, posits that alignment between the "patterns of relevant contextual, structural, and strategic factors" (Doty et al., 1993, p. 1196) leads to superior firm performance and misalignment results in performance erosion. In information systems, much effort has been devoted to studying how strategic alignment of information technologies affects organizational performance and Oh & Pinsonneault (2007) provide a good overview of these studies. In general, prior empirical research has shown that IT/IS alignment is positively associated with general performance measures such as perceived firm performance (Kearns & Lederer, 2001; Sabherwal & Kirs, 1994) and financial performance (Chan et al., 1997). In this research, we specifically consider environmental firm performance, mainly measured in terms of carbon emissions and energy efficiency and, following (Chan et al., 1997), we consider that a realized IS Strategy will have a direct impact on firm performance. We further consider that the realization of an Environmental IS Strategy is expressed through the implementation and use of the IT applications and information systems presented previously in Table 1.

Moreover, in the literature pertaining to organizations and the natural environment, several studies have been conducted to examine the relationship between environmental practices and performance (Doonan et al., 2005; Shi et al., 2012; Shrivastava, 1995; Zhu & Sarkis, 2004; Zhu et al., 2005). Some research efforts have specifically described the positive impact of using information systems for reporting and measurement of environmental business practices (Rikhardsson, 1998; Shaft et al., 2001). Moreover, the positive relationship between information systems and firm performance has been extensively debated in the information systems literature (Benitez-Amado & Walczuch, 2012; Bharadwaj, 2000; Caldeira & Ward 2003; Clemons, 1991; Jarvenpaa & Leidner, 1998; Santhanam & Hartono, 2003).

Based on the above and considering that the implementation and use of environmental monitoring information systems currently consists the main expression of an Environmental IS Strategy, we formulate the following research hypothesis:

H.1. An Environmental IS Strategy will positively affect a firm's environmental performance

2.4.2.3 The relationship between environmental business strategy, environmental IS strategy and performance

A significant body of literature on organizations and the natural environment has discussed how the environmental concerns are incorporated in a firm's strategy (Aragon-Correa & Sharma, 2003) and investigate how environmental strategies are developed (Bansal & Roth, 2000). Environmental strategies are perceived either as a continuum ranging from reactive to proactive strategies (e.g. Aragon-Correa, 1998; Sharma, 2000) or as distinct strategies (Banerjee, 2002; Dyllick & Hockerts, 2002; Hart, 1995). According to Banerjee (2002), environmental strategy is “the extent to which environmental issues are integrated with a firm's strategic plans and it is differentiated in corporate and marketing strategy”. Environmental corporate strategies pertain to the kind of businesses a firm should enter to meet its enterprise strategy goals, to the strategies leading to product differentiation or targeting niche markets and to functional level strategies as modification of operating procedures within different functions, such as advertising or sales (Banerjee, 2002). In this case environmental concerns are integrated with the corporate strategic planning process. Environmental marketing strategies, on the other hand, pertain to “targeting the environmentally conscious consumer segment and developing new environmentally friendly products” (Banerjee, 2002).

Hart (1995) and Dyllick & Hockerts (2002) have also proposed two more hierarchies of environmental strategies based on the impact that their implementation has on the environment and the extent of the organizational changes required in order to implement them. According to Hart (1995), environmental strategies could be classified into pollution prevention and control, product stewardship, and sustainable development. Dyllick & Hockerts (2002) propose three strategies: eco-efficiency, eco-equity and eco-effectiveness.

Considering the fact that firms are interested in developing an environmental IS strategy not only for increasing their environmental efficiency but also for enhancing their public image and responding to their customers' increasing environmental awareness, we consider that the two types of environmental strategy that Banerjee (2002) proposed make a good fit to our study. Moreover, it is also supported by a previous differentiation of strategies that are labeled as ‘‘supplier management for risks and performance’’ and ‘‘supply chain management for sustainable products’ (Seuring & Müller, 2008) and have as objective the ‘‘greening the supply process’’ and ‘‘product based green supply’’ respectively (Bowen et al., 2001).

Many previous studies have investigated the role of environmental strategies on applying environmental practices (González-Benito & González-Benito, 2006; Teixeira, 2011), green supply chain practices (Chan et al., 2012) and environmental sustainable development (Bansal & Hunter, 2003; Shrivastava, 1995). Moreover, there is another stream of research, focused more on the implementation of green information systems (Jenkin et al., 2011), that explores the relationship between strategies and the actual implementation of green information systems (Chen et al., 2008; Setterstrom, 2008; Yang et al., 2007). While some of these studies rely on the resource-based approach, in this paper we adopt the contingency approach and posit that in order to have a positive impact on firm performance the realization of an IS strategy should derive from a respective business strategy.

Based on the above and on the discussion associating IT applications and information systems to the realization of an Environmental IS Strategy above, we formulate the following hypotheses:

H.2. Environmental Corporate Strategy will positively affect the development of an Environmental IS Strategy

H.3. Environmental Marketing Strategy will positively affect the development of an Environmental IS Strategy

Apart from the indirect impact that a firm's environmental business strategy has on environmental performance through the realization of an aligned IS strategy, we consider that an environmental business strategy also has a direct impact on environmental performance. A significant body of literature has explored the relationship between environmental strategies and organizational and environmental performance (e.g. Baker & Sinkula, 2005; Benitez-Amado & Walczuch, 2012; Judge & Douglas, 1998; Klassen & Whybark, 1999). By using the resource-based perspective, previous efforts have argued that there is a positive relationship between environmental strategies and organizational and environmental performance when complex capabilities are developed (Baker & Sinkula, 2005). Hart (1995) supports that specific capabilities could be developed due to innovative environmental strategies and these could have competitive advantage as a result. Sharma & Vredenburg (1998) found that the implementation of a proactive environmental strategy could bring business benefits towards the development of specific organizational capabilities. Overall, this stream of research considers the ability of integrating environmental issues to corporate strategy and developing environmental strategies as an opportunity for a firm to develop valuable and not easily imitated organizational capabilities that could improve a firm's performance and bring competitive advantage and argue that there is a direct positive relationship between environmental strategy and environmental performance.

Moreover, Klassen & McLaughlin (1996) argue that there is a positive linkage between environmental management, which is an integrative component of the environmental strategy, and improved environmental and financial performance. Judge & Douglas (1998) support that the level of integration of environmental concerns in a firm's strategy is positively related both to financial and to environmental performance. Previous studies have also empirically tested the effect of proactive environmental strategies on environmental performance and economic performance (e.g. Russo & Fouts, 1997; Spicer, 1978).

Based on the above, we consider that an environmental business strategy, expressed through various other environmental practices and not just an aligned IS strategy, can serve to improve environmental performance and we formulate the following hypotheses:

H.4 Environmental Corporate Strategy will positively affect a firm's environmental performance

H.5 Environmental Marketing Strategy will positively affect a firm's environmental performance

Figure 1 depicts the research model of the study.

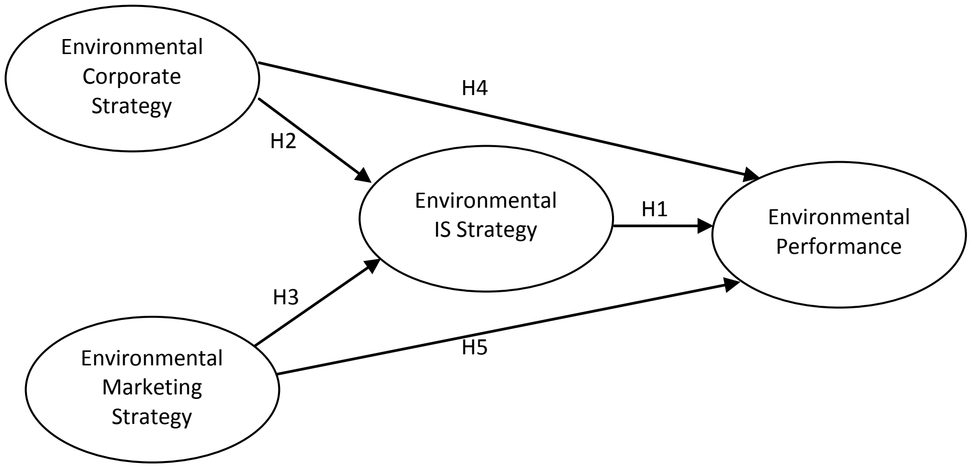

Figure 2.9: The research model

2.4.3 Results and Discussion

To test our research hypotheses, a survey approach was followed, using the firm as unit of analysis. A detailed questionnaire has been used as research instrument (Appendix A). The survey ran for three months and was addressed to firms in the fast-moving consumer goods (FMCG) industry. We chose to focus on this industry due to their extensive interest in addressing various environmental issues. The survey ran from March 2012 to June 2012. A total of 75 valid questionnaires have been collected. To analyze the questionnaire data, examine the research model and test the hypotheses, a variety of analytic techniques and tools was used. SPSS software was used to organize the data and run preliminary descriptive analyses. The examination of the research model and the hypotheses testing was performed using the Structural Equation Modelling (SEM) technique using Partial Least Squares (PLS). For brevity reasons, the detailed process of data collection and analysis is presented in Appendix B.

Initially, the descriptive statistics of the constructs are shown in Table 2.3.

Table 2.3: Descriptive Statistics

Constructs	*Descriptive Statistics*	
	Mean	*Standard Deviation*
Environmental Corporate Strategy	5.20	1.61
Environmental Marketing Strategy	4.30	1.80
Environmental Performance	5.69	1.79
Environmental IS Strategy	5.49	1.84

In PLS, the strength and the significance (or insignificance) of each structural path or hypothesis can be examined. PLS calculates a path coefficient or a beta value (β) which indicates the strength of the path and signifies the unique contribution that the independent variable makes in explaining the variance in the dependent variable. In addition, in PLS the statistical significance (or insignificance) of each hypothesis or path can be examined by applying a bootstrapping analysis. Figure 2 presents the results of the PLS path analysis (path coefficients (PC), T-values and R2).

The hypothesis that links Environmental Corporate Strategy and Environmental IS Strategy (H2) is supported and approximately 12% of the variance of the realized Environmental IS Strategy is captured by the variables in the model. Moreover, Environmental Corporate Strategy and Environmental IS Strategy are related to Environmental Performance and Hypotheses H1 and H4 are supported. However, the hypothesis that links Environmental Marketing Strategy with the realized Environmental IS Strategy (H3) and with Environmental Performance (H5) are not supported. Besides, 39% of the variance of Environmental Performance is captured by the factors that are included in the model.

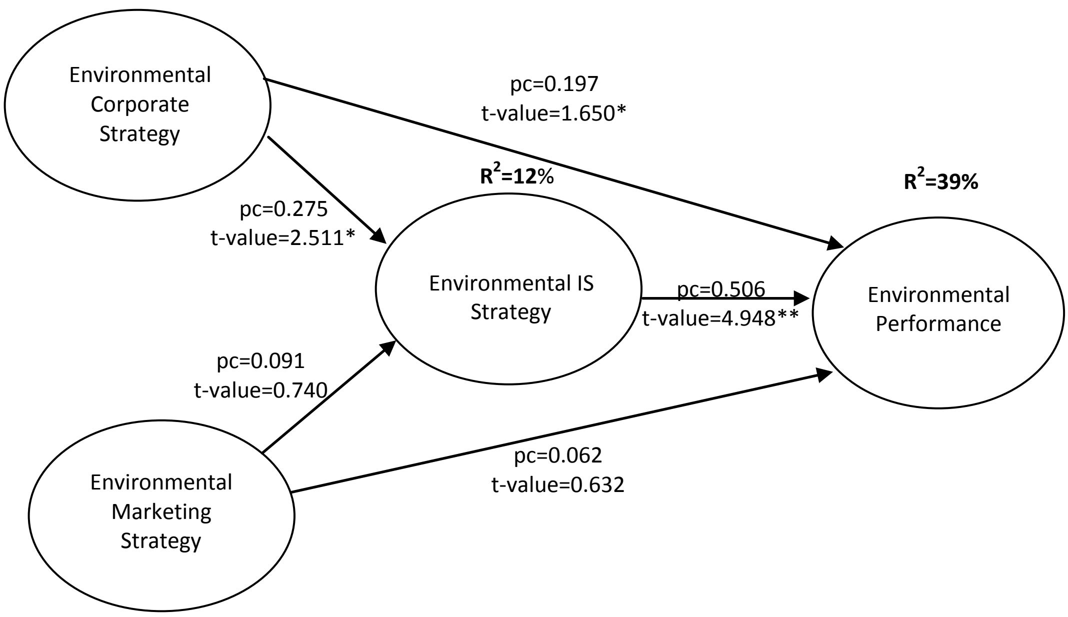

Figure 2.10: ***PLS structural model***

*Note: *P<0.10, **P<0.05*

Results indicate that there is a significant positive relationship between an environmental IS strategy, as currently materialized through the use of energy and carbon management systems and a firm's environmental performance. Moreover, this relationship is stronger than the direct relationship between a firm's environmental corporate strategy and environmental performance, meaning that with the presence of an environmental IS strategy; the impact of other environmental practices on a firm's perceived environmental performance is lessened. This may mean that the use of energy and carbon management systems have indeed a significant impact on reducing a firm's environmental performance indicators, such as carbon emissions and energy consumption, or that managers' perceptions of environmental performance are higher due to better accountability provided by a monitoring system.

We were also expecting to find a positive relationship between a firm's environmental business strategy and the realization of an environmental IS strategy. Having used the distinction of an environmental business strategy into corporate and marketing environmental strategy, as proposed by Banerjee (2002), we have come across an interesting finding. While results have shown that there is a significant positive relationship between corporate environmental strategy and an environmental IS strategy, as expected, this relationship is not strong when a firm's environmental strategy is driven by marketing motives. This can be explained by the fact that firms who have established an environmental corporate strategy and have been engaged in various environmental activities are more likely to initiate the implementation of environmental monitoring information systems. To the contrary and despite the fact that energy and carbon management systems will enable firms to measure the environmental impacts of their products and to communicate this information to their customers, it seems that environmental marketing issues have not yet been a major driver behind the adoption of these systems. Besides, more of the energy and carbon management systems except from the Life Cycle Assessment (LCA) tools are not used to support environmental arguments in marketing communications.

The findings of this study also support prior research findings proposing that a higher competitive position enabled by IT-business alignment is more likely in innovative and proactive firms (e.g., Tallon, 2000; Sabherwal et al., 2001). Proactive and innovative firms often both invest in IT and implement environmental strategies. To the extent that IT strategy is well aligned with the environmental strategy, IT capability may be a key enabler of the implementation of the firm’s environmental strategy and to increase its competitiveness (Benitez-Amado & Walczuch, 2012).

To sum up, the findings of this research provides first empirical evidence on the positive impact of energy and carbon management systems on a firm's environmental performance. However, more research should be conducted in order to identify the mechanisms through which Energy and Carbon Management Systems impact on environmental performance. Energy and Carbon Management Systems are expected to support sense-making, enable and enhance decision-making and knowledge creation in terms of environmental impacts within organizations (Butler, 2011; vom Brocke & Seidel, 2012; Seidel et al., 2013; Shrouf & Miragliotta, 2015). However, there is limited research on this topic.

2.5 Research Objective and Questions

The previous sections identify the gaps both in the pertinent literature and the industry challenges related to energy and carbon management in the supply chain. They reveal the need of an emerging class of systems focusing on the energy and carbon management, called herein as Energy and Carbon Management Systems (ECMS). ECMS aim to contribute to the implementation of environmentally sustainable supply chains by supporting energy and carbon management, environmental-aware decision-making and the implementation of environmentally sustainable supply chain practices. According to Melville & Whisnant, (2014), an ECMS is defined as "*a type of enterprise information system that takes as inputs various types of environmental data (e.g., electricity and fuel use, furnace combustion, emission factors, employee commuting, and air travel), processes that data into usable information, (e.g., megajoules of energy, GHG emissions), and provides enhanced functionality (e.g., automated reporting, managerial dashboards, supply-chain analytics, and workflow management).*"

More specifically, these systems should be able to capture energy and carbon related information from energy consumption measurement infrastructures, to integrate and interoperate with a company's existing enterprise systems (e.g., ERP, WMS, MES), to interpret and integrate the data received from various sources, to exchange data with the enterprise systems of supply chain partners and support decision making in the supply chain.

Considering the above, the starting point of this research is on advancing the understanding of “how” to design and implement an energy and carbon management system in the supply chain and aims to shed light on their impact on the implementation of environmentally sustainable supply chains.

The integration of the various information flows needed to enable energy and carbon management is a critical aspect for the design and implementation of ECMS. Therefore, in our study we elaborate on the integration of the various information flows and we consider ECMS as a specific class of an EMIS that focuses on the integration of various information flows, includes KPIs that provides an integrated view both operational and environmental ones and expands at the whole supply chain.

More specifically, the following questions arise:

- Which are the business requirements for energy and carbon management in the supply chain?
- Which are the information flows needed in order to support energy and carbon management in the supply chain?
- How can energy and carbon management systems integrate the information flows needed in order to support energy and carbon management?
- Which are the necessary components that specify energy and carbon management systems?
- Which are the design and implementation principles that will guide the design and implementation of energy and carbon management systems?
- How does the design of energy and carbon management systems support energy and carbon management?
- How does the design of energy and carbon management systems support environmental - aware decision-making and the implementation of environmentally sustainable supply chain practices?

As the aim of this thesis is to provide answers to the research questions that are independent of the application domain of energy and carbon management systems, we also investigate the effect of contextual implementation challenges, such as data quality and availability, data capture and integration, environmental performance metrics and collaboration and information sharing on the design of these systems. Therefore, we conclude to two more questions:

- Which contextual factors affect the design and implementation of energy and carbon management systems?
- How do the contextual factors affect the design and implementation of energy and carbon management systems?

Summarizing the above, the main research questions of this thesis are formulated as following:

- Q1. What is the design of energy and carbon management systems in the supply chain?
- Q2. How do energy and carbon management systems impact the development of environmentally sustainable supply chains?

It is emphasized that this thesis will provide answers to the research questions that are independent of the application domain of energy and carbon management systems.

3 RESEARCH METHODOLOGY

3.1 Introduction

The aim of this chapter is to present the research methodology employed in order to address the research objectives and answer the research questions. Given our research objective and the aforementioned research questions, we adopt as methodological backbone the design science paradigm and we consider both an artifact and an information systems design theory (ISDT) as outcomes of this study. Thus, initially we present the 'design-science research methodology process model' (Peffers et al., 2007). Then, we present the specification framework for ISDT suggested by Gregor & Jones (2007) and the components of an ISDT in detail. For collecting data for the various steps of Design Science Research Steps, four different cases studies are selected and presented. Energy and Carbon Management is handled separately for manufacturing and for warehousing and transportation activities, as this allows for analysis and details focused on each supply chain activities specifics. Therefore, two of these cases cover manufacturing activities and represent textile industry and the other two cover warehousing and transportation activities and represent Fast Moving Consumer Goods Industry. Their specificities are also discussed in this chapter (Section 3.4.2 and 3.4.3).

3.2 Design Science Research Approach

Given our research objective and the aforementioned research questions, we adopt as methodological backbone the design science paradigm as it is an approach that is recommended on addressing the issues related with the prescription of a new class of information systems such as Energy and Carbon Management Systems. The outcome of a decision science research study could be both an artifact and an information systems design theory (ISDT) (Kuechler & Vaishnavi, 2012). Therefore, particularly in an emergent field as Energy and Carbon Management Systems both an exemplar artifact and an ISDT is important to offer theory-based guidance for its design to researchers and practitioners alike and also implementation guidelines.

More specifically, Design Science Research (DSR) is one of the two research paradigms that Hevner et al. (2004) have recognized. The other research paradigm, called as behavioral-science paradigm, has its roots in natural science research methods and focuses on identifying and explaining the underlying regularities of phenomena or on interpreting human experiences and discourse (Romme, 2003). It seeks to develop and justify theories (i.e., principles and laws) that explain or predict organizational and human phenomena surrounding the analysis, design, implementation, management, and use of information systems. On the other hand, the **design-science paradigm** has its roots in engineering and the sciences of the artificial (Simon, 1996) guidelines, design principles and technical capabilities through which the analysis, design, implementation and use of information systems can be effectively and efficiently accomplished (Denning 1997). Such artifacts are not exempt from natural laws or behavioral theories. To the contrary, their creation relies on existing kernel theories that are applied, tested, modified, and extended through the experience, creativity, intuition, and problem solving capabilities of the researcher (Markus et al. 2002; Walls et al. 1992). Such artifacts vary from constructs (vocabulary and symbols), models (abstractions and representations), methods (algorithms and practices), and instantiations (implemented and prototype systems) (Hevner et al., 2004; Hevner &

Chatterjee, 2010). The development of design knowledge, for instance, in the form of reusable design patterns, principles, or guidelines, is of high importance to both IS research and practice (Kuechler & Vaishnavi, 2008; Winter, 2008). Goes (2014) highlights the absence of design science research in Top Journals and subscribes to the notion that the IS field needs more design science research. Aligned with the above perception is the recent call for papers for EJIS special issue on Exemplars and criteria for applicable design science research. Therefore, the design science research paradigm increasingly diffuses into the IS community (Baskerville, 2008; Lee & Nickerson, 2010; Winter, 2008) and has gained increasing recognition over the last several years (Baskerville, 2008; Lee & Nickerson, 2010).

Recent research has proposed guidelines for conducting and reporting DSR (Aier et al., 2011; Baskerville et al., 2015; Gregor & Hevner 2013; Hevner et al. 2004; Kuechler & Vaishnavi 2012; March & Storey 2008; Peffers et al. 2007). In order to develop theory, its respective components and the artifact, we adopt the 'design-science research methodology process model suggested by Peffers et al. (2007). We choose a problem-centered research initiation (Peffers et al. 2007) due to dual origin of our research problem (both academia and business practice).

In the following, we describe the implementation of each subsequent step within the research project and the employed methods (Figure 3.1).

Step 1: Problem identification and motivation. In this step, we defined the specific research problem and justify the value of a solution on energy and carbon management in the supply chain. As described in Section 2 (Research Background), our research emanates from problems that we observe in both the practice and the literature. The basis for the identification of the research needs and gaps and the motivation in the area of energy and carbon management in the supply chain was a detailed mapping of the state-of-the-art of 'future research needs' by conducting a comprehensive literature review in both research and practitioners documents. Regarding business practice, we rely on the industrial exploratory research that included workshops and semi-structured interviews with industry experts as well as a survey.

Step 2: Define the objectives for a solution. Here, we infer the objectives of a solution from the problem definition and knowledge of what is possible and feasible. We conduct the analysis of user requirements in close collaboration with relevant corporate decision makers, who are responsible for supply-chain management, environmental management, and reverse logistics. In order to achieve the objective of this step, the following methods were employed: Several meetings and semi-structured interviews with four major companies, on-site observation, viewing users as they work and taking notes of the activity which takes place, an industry survey on environmental performance, meetings with industry experts and focus-group discussions on sustainability through Industrial Interest Group (IIG).

The industrial context of our research includes the sectors of 'Textile & Clothing' and 'Fast Moving Consumer Goods' (FMCG) and involves manufactures, suppliers and retailers (see Section 3.4). Moreover, to set specific objectives and coherently advance the design and validity of or theory, we worked separately for manufacturing issues, with two representative textile organizations interested in energy-efficiency (a leading textile manufacturer and an international clothing company) and for supply chain issues with two representative FMCG organizations interested in sustainability (a retailer and a major food manufacturer).

Step 3: Design and development. The objective of this activity is to create the artifact. The artifact in our study is an energy and carbon management system. The design and development process followed that of an IS development project. It started with a requirements-gathering process (Step 2), in which a diverse set of potential end users participated (as presented before), resulting in requirements documentation, which was later used for designing a detailed technical architecture.

Step 4: Demonstration & Evaluation: This step tests the developed artifact concerning its practical feasibility and its contribution to close the identified research gap. A rigorous design evaluation may draw from many potential techniques, such as analytics, case studies, experiments, or simulations (see Hevner et al. 2004) and naturalistic evaluations (Carlsson & Johansson, 2010). Further sources for methods of evaluation include Pries-Heje et al. (2008) and Sein et al. (2011). We used an observational design evaluation by using the Field Study approach.

In this line of thinking, we use the context of Fast Moving Consumer Good and textile industry and more specifically four companies (see section 3.3) and we developed a system and the developed artifact and the required software (interfaces with existing systems) and hardware elements (e.g.. energy sensors) were installed in these two companies. Moreover, a process for collecting, processing and validating the actual data that were necessary was deployed. The demonstration details are presented in Sections 5.3 and 6.3.

The evaluation activity involves the identification of the issues that appear during the demonstration and comparing the objectives of a solution to actual observed results from use of the artifact in the demonstration and provide a proof of concept that will guide further research. The technical and data related issues that were identified were lead to a new phase of design and development. Moreover, a technical evaluation of the system was conducted and it was also evaluated in order to explain whether the non-functional requirements are met (Appendix F). Moreover, a further evaluation of the artifacts was conducted by selected employees working in our study cases in order to gain feedback about the efficiency of the system. They interacted with the system by executed a set of pre-defined scenarios and then completed a questionnaire for evaluation purposes.

Step 5 – Communication: With this thesis, the published papers and workshops conducted, we communicate the results of the research to both the academic community and practitioners from a technical and a management point of view. This “enables practitioners to take advantage of the benefits offered by the artifact and it enables researchers to build a cumulative knowledge base for further extension and evaluation” (Hevner et al. 2004, p. 90).

The artifact generation is concrete based on an incremental and iterative refinement approach that switches between construction phases and evaluation (Markus et al., 2002). More specifically, Demonstration & Evaluation in real-world settings was conducted in two phases so that the first phase could give feedback to the second round of defining the objectives for a solution and the design and development. During this iterative process, we identified new design and implementation principles derived from the actual implementation of the artifacts, to inform ISDT components and enhance its validity. This round was strongly guided by the implementation challenges imposed by the environmental data availability, the different data granularity levels, the poor data quality, the dependencies and coordination problems due to the need of aligning inputs from multiple partners, the technical integration issues and the absence of automation mechanisms; evidently, these challenges reveal specific features to be implemented in order to ensure the efficacy of such systems in a real-world context.

As mentioned above, the outcome of a decision science research study could be both an artifact and an information systems design theory (ISDT) (Kuechler & Vaishnavi, 2012). Gregor (2006) affirms that knowledge on the design of an IT artifact also exhibits the characteristics of a theory. Two extensive reviews of design science literature (Gregor, 2006; Venable, 2006) illustrate that theory and theorizing have a role in the IS discipline that is distinct from pragmatic design efforts that consider artifacts as the main research contributions. The design theory is considered to be prescriptive knowledge as opposed to descriptive knowledge, which encompasses the other types of theory in the Gregor taxonomy. ISDT, as introduced by Walls et al. (1992,2004), is a set of primarily prescriptive statements describing how a class of artifacts should behave and how they can be constructed. Theory adds new knowledge to a community and addresses ill-defined problem spaces that do not yet have established design practices. Design theory must bring novel values and goals because an ill-defined problem space "does not contain sufficient information to enable the designer the means of meeting those requirements simply by transforming, reducing, optimizing or superimposing the given information alone" (Archer 1984, p. 384).

There have been attempts to how to define an ISDT (Walls et al., 1992). A research strand on the development of ISDT adopts the Walls et al. (1992) approach (e.g. Markus et al., 2002). However, Gregor & Jones (2007) extend their approach on the specification of information systems design theories (ISDT) by drawing on other streams of thought on design research and design theory. They highlight the importance of the notion of a design instantiation as stressed in the design science literature, except as a test of a theory. Particularly in an emergent field as Energy and Carbon Management Systems both an exemplar artifact and an ISDT is important to offer theory-based guidance for their design to researchers and practitioners alike, as well as the implementation guidelines. Therefore, we use the specification framework for ISDT suggested by Gregor & Jones (2007) where they have expanded the initial Walls et al., (1992) approach by incorporating the notion of artifact instantiation. More specifically, they identified eight separate components of design theories: (1) purpose and scope, (2) constructs, (3) principles of form and function, (4) artifact mutability, (5) testable propositions, (6) justificatory knowledge (kernel theories), (7) principles of implementation, and (8) an expository instantiation (Presented in Section 3.2).

The aforementioned steps that Peffers et al., (2008) proposed contributed not only to the development of an artifact but also to the systematically formulation of the basic components of ISDT (Figure 3.1) based on an incremental approach. Below, we summarize how the ISDT was formulated following these steps. Initially by conducting the first two steps, we define the design's purpose and scope. Then we derive a set of design requirements from justificatory knowledge that give guidance to the subsequent specification of our design and we identify the theory's core constructs. The mutability aspect was informed based on the outcomes of the literature review but also with the main findings of preliminary research. Moreover, we develop a set of testable propositions that inform the evaluation of the proposed design. By using as starting point the above, we work closely with the four companies (Step 2 and 3) in order to design and develop Energy and Carbon Management System artifacts and to inform the theory's purpose and scope, design requirements, principles of form and function, core constructs. Subsequently in step 4, we demonstrate the two artifacts and concluding to a set of design and implementation principles that inform principles of form and function and principles of implementation components of design theory and guide the second round of design (Step 2 and 3). Then, we demonstrate we provide empirical evidence on the testable propositions (Step 4). The mutability aspect of the design theory is formulated and discussed at step 4.

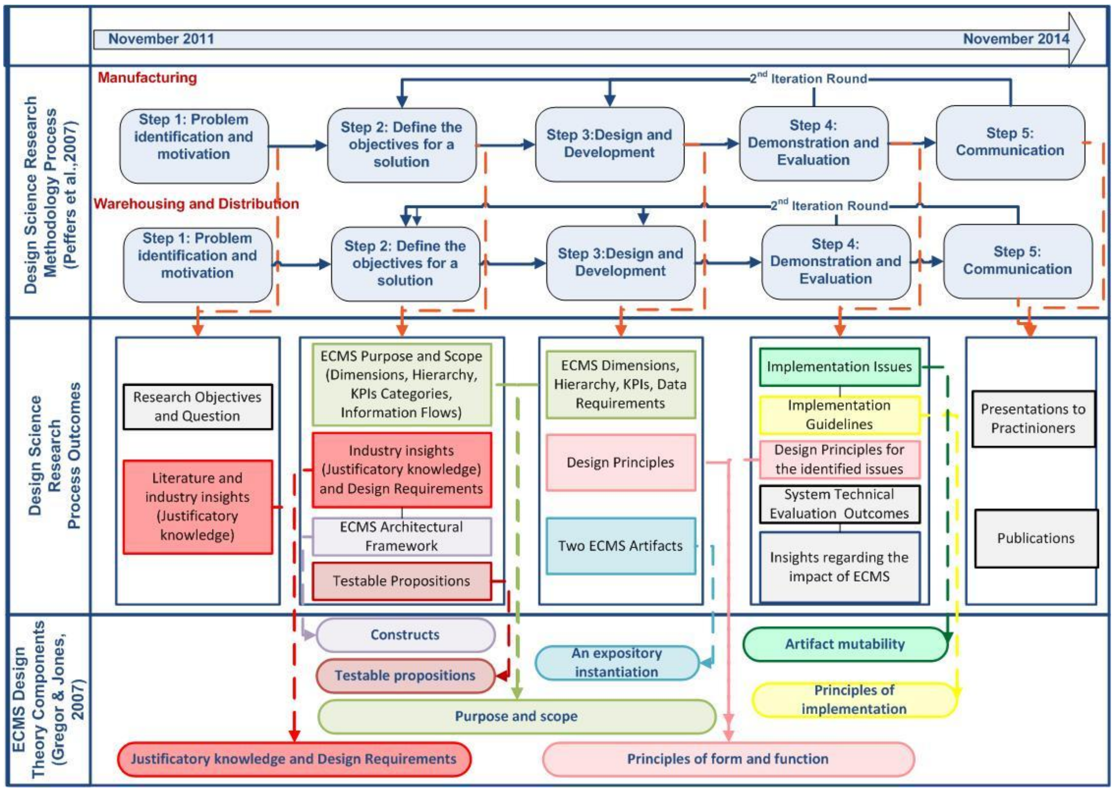

Figure 3.1: Research Methodology (Top: DSR Process Steps, Middle: DSR Outcomes, Bottom: Information Systems Design Theory Components)

3.3 Information Systems Design Theory Components

As discussed above, in our research we used the ISDT specification approach proposed by Gregor & Jones (2007) in order to further explicate the structural components that are needed to specify and communicate a design theory for Energy and Carbon Management Systems:

The eight ISDT components are the following (Gregor & Jones, 2007):

1. Purpose and scope

This design component says “what the system is for.” or the set of meta-requirements or goals that specifies the type of system to which the theory applies and in conjunction also defines the scope, or boundaries, of the theory. These theory requirements are meta-requirements; they are not the requirements for one instance of a system, as would be the case if there was a need to build a single system in industry. The aim is to develop a design theory that is suited to a whole class of artifacts that are typified by these requirements.

2. Constructs

The representations of the entities of interest in the theory (Dubin’s “units”) are at the most basic level in any theory. These entities could be physical phenomena or abstract theoretical terms. A feature of design theories for information technologies is that a single construct in a theory can represent a sub-system that has its own separate design theory.

3. Principles of form and function

This component refers to the principles that define the structure, organization, and functioning of the design product or design method. The shape of a design product is seen in the properties, functions, features, or attributes that the product possesses when constructed. In a sense, this component gives an abstract “blueprint” or architecture for the construction of an IS artifact. However, it is important that a design principle is formulated sufficiently abstract to leave some space for different instantiations in different contexts that share the defined boundary conditions.

4. Artifact mutability

The changes in state of the artifact anticipated in the theory, that is, what degree of artifact change is encompassed by the theory. Specifying the degree of mutability of designed artifacts refers also to the changes that affect the basic form or shape of the artifact, for example, in allowing for a certain amount of adaptation or evolution.

5. Testable propositions

An ISDT can give rise to testable propositions or hypotheses about the system or tool to be constructed. These propositions can take the general form: “If a system or method that follows certain principles is instantiated then it will work, or it will be better in some way than other systems or methods.” Testing theoretical design propositions is demonstrated through an instantiation, by constructing a system or implementing a method, or possibly in rare cases through deductive logic (Gregg et al., 2001; Hevner & March, 2003).

6. Justificatory knowledge (kernel theories)

This component provides the justificatory, explanatory knowledge that links goals, shape, processes, and materials. Some knowledge is needed of how material objects behave, so as to judge their capabilities for a design. The underlying knowledge or theory from the natural or social or design sciences that gives a basis and explanation for the design (kernel theories). Justificatory knowledge does not only come from theories but also from practitioners insights.

7. Principles of implementation

A description of processes for implementing the theory (either product or method) in specific contexts. The provision of implementation principles in their design theory would mean specifying explicitly the steps a project manager would take to incorporate these parameters into the policy formulae in implementing the policy in a project.

8. An expository instantiation.

A physical implementation of the artifact that can assist in representing the theory both as an expository device and for purposes of testing. The construction of an instantiation as proof-of-concept and the development of specific methods for building further instantiations could come later. The credibility of the work is likely to be enhanced, however, by provision of an instantiation as a working example. The credibility of the work is likely to be enhanced, however, by provision of an instantiation as a working example. Some particular innovative ideas may have merit, despite the lack of an instantiation.

3.4 Cases Studies Background

Our study enjoys a broad scope regarding the energy and carbon management, ranging from the supplier of raw materials to the point of sales. However, energy and carbon management for manufacturing is recommended to be handled separately, as this allows for analyzing the manufacturing specifics (The Consumer Good Forum, 2012). Thus, to set specific objectives and coherently advance the design and validation of our architectural framework, we worked separately for manufacturing issues, with two representative textile organizations interested in energy-efficiency (a leading textile manufacturer and an international clothing company) and for supply chain issues with two representative FMCG organizations interested in sustainability (a retailer and a major food manufacturer) (Presented in Section 3.4.1). These four cases were selected in order to:

a) cover the whole supply chain and examine differently manufacturing and supply chain cases (including warehousing and transportation) in order to capture their specificities,

b) investigate the application of energy and carbon management in industries with different objectives for sustainability e.g. textile industry is most cost-driven on the implementation of energy and carbon management and FMCG industry is also interested on developing collaboration relationships and addressing customer concerns towards energy and carbon management, and

c) cover the various contextual settings that are related with the implementation challenges discussed in the previous sections.

More specifically, they provide different aspects of data quality and availability, data capture and integration, Environmental Performance Metrics and Collaboration and Information Sharing that will reveal specific features to be implemented in order to ensure the efficacy of such systems in a real-world context. We initially describe shortly the context under which the system was designed and implemented and the aforementioned aspects. Further details on the specification and challenges on the manufacturing and the supply chain challenges as they rose during the addressed in the two cases are also presented in more detail in Sections 3.4.2 and Section 3.4.3.

3.4.1 Case Studies Description

Starting from manufacturing, the textile manufacturer is one of the oldest textile industries. It is an Italian Medium Enterprise with 210 employees and a production of more than 700.000 meters of fabrics. It is currently interested in enhancing the energy efficiency in manufacturing and collaborative supply chain practices. Despite its interest, the firm currently collects energy data only for accounting purposes based on energy bills. Due to the absence of sensor enabling automatic energy monitoring, it uses the Energy Audits as a systematic procedure in order to gain a suitable knowledge of the energy consumption profile of an industrial activity/plant and to identify and quantify energy saving opportunities mainly from the viewpoint of costs and benefits. Let us call this manufacturer as 'Case A'.

Our 'Case B' is the clothing company with 735 employees in Germany alone and an annual turnover of 184 million Euros. Another 2000 people are employed in Eastern Europe for the manufacturing of garments. It has also 109 retail stores in 58 countries and more than 1500 additional up-market fashion stores around the world. As its energy costs remain high, it is especially interested in reducing the energy consumption. In this case, extensive energy consumption data are available (by both energy audits and real-time sensor monitoring) and they had only been used to analyze the accrued energy consumption about long time periods like months and years and but cannot be mapped to production orders and final products.

'Case C' is a major Greek retailer whose internal mechanisms portray an environmentally-aware enterprise. Its supply chain consists of a central warehouse and a total of 94 stores (53 supermarkets and 41 Cash & Carry). The central warehouse stores the products received from most suppliers (more than 600) and distributes them to the stores using its own fleet of vehicles. It has already deployed various environmental-friendly practices, like ambient sunlight for daytime lighting in buildings.

Last, 'Case D' is a multinational food manufacturer and one of the main suppliers in the FMCG sector, having an environmentally-aware profile. It has an extensive and complex supply chain network with presence in Europe (Italy: 5 mills, 9 production plants; rest of Europe: 3 mills, 6 production plants), America (1 mill, 2 production plants), Asia and Oceania. Its distribution network is vast, with partners in more than 100 countries. It has implemented several environmental practices over the years such as energy saving programs, installation of two co-generation plants, LCA methods and Environmental Product Declaration (EPD), business intelligence and sustainable packaging in its logistics.

These four cases were selected as they provide different aspects of data quality and availability, data capture and integration, Environmental Performance Metrics and Collaboration and Information Sharing that will reveal specific features to be implemented in order to ensure the efficacy of such systems in a real-world context. Table 3.1 highlights these aspects by summarizing the actual data and the systems that provide them in the four cases.

Table 3.1: Case settings Requirements of Energy and Carbon Management

	Case A	**Case B**	**Case C**	**Case D**
Scope	Manufacturing	Manufacturing	Supply Chain	Supply Chain
Energy Consumption Data Availability	Limited data from energy audits	Limited data from energy audits	A building management system in one store (recording consumption every 5 secs) and energy bills for all other stores	Energy sensors that could not be integrated, as they did not have an interoperable API.
Fuel Consumption Data Availability	Not applicable	Not applicable	Actual vehicle refills are available in ERP	Not available as an external 3PL provider is used
Processes flow data	MES keeps information about production processes	A new ERP/PPD keeps data on production processes	Warehouse management systems keeps daily data on inventories and distributions processes	ERP stores suppliers' transactions (e.g., ordering). No data on distribution because of an external 3PL provider
Contextual flow data	Stored in ERP	Stored in ERP	Stored in ERP	Stored in ERP
Data exchange Mechanisms	N/A	N/A	They have already been installed for other cases.	No such mechanisms are installed

3.4.2 Case Studies Context

<u>Manufacturing Context</u>

We initially describe shortly the context under which the system was designed and implemented and then we discuss the specificities of manufacturing. In general, the textile manufacturing processes are characterized by diversities covering various production aspects e.g. type of machines, process steps and the respective production times, articles and production orders and consequently a great complexity of monitoring the production workflow. For example, machines can operate in a batch mode (washing machines) or in continue mode and the processing times vary widely extending from a couple of minutes per lot (e.g. some finishing processes) to many days (e.g. weaving). Moreover, the fashion trends diversify the article mix and the quantity of the production orders. All the aforementioned diversities have as result many energy consumption fluctuations that are responsible for increased energy costs and should be moderated. For example, the utilization of the machines, which often are specialized to certain articles, varies significantly and the energy reduction potential by reducing the stand-by times is significant.

Within the context of manufacturing, the monitoring of energy consumption is focused on the energy consumed that is being divided into direct and indirect energy (Seow & Rahimifard, 2011). Direct Energy (DE) refers to the actual energy used by various processes (e.g., weaving, finishing) required for manufacturing the product. Indirect Energy (IE) on the other hand refers to energy consumed by activities that are not directly involved in manufacturing of the product. These are normally energy drawn by lightings, cooling/heating and ventilation systems. Moreover, a prevalent energy consumption monitoring practice is based on energy vectors that are produced based on aggregated historical data. Therefore, if actual energy consumption measurements are absent, the energy vectors are used in order to estimate energy consumption and support environmental performance monitoring. The carbon footprint at the various levels of analysis is derived based on the energy consumption.

Below, we summarize the specificities in the textile manufacturing that may affect the design and the implementation of the ECMS:

- The energy consumption is diversified in different categories. As presented above, we identified the direct and indirect energy consumption. Moreover, it could be differentiated in actual, normal or planned energy consumption based on the data used for the estimations. The actual energy consumption is based on measured data that are provided either by energy monitoring infrastructures (e.g. sensors) or by energy suppliers. The normal energy consumption is normalized energy consumptions that can be derived by evaluating measured historical data using suited reference values. The normal data are usually expressed in the form of energy vectors. The plan energy consumption is calculated based on normal data and refer to future energy consumptions.
- The energy consumption is differentiated at the different production phases but even in machine level. In each machine, three phases are identified: a) Load and setup: the batch is inserted into the machine and the machine's setup configuration is performed, b) Production: it is the actual production of the batch, c) Unload and cleaning: the batch is unloaded from the machine and a cleaning is performed before the new production. Therefore, for each machine information about the three different phases should be kept.
- The production seasonality, that is responsible for energy consumption fluctuations, affects the production processes patterns by creating new production demands and increases the complexity of monitoring production processes workflow and ensuring data quality and integration.
- The items (e.g. products/articles) that are monitored are not final products and a mapping between higher-level items with their components is required. The bill of material, which actually lists all the components of every item and, recursively, list the sub-components as a component of components, covers the aforementioned need. However, monitoring the transformation of raw materials or semi- finished products is critical in order to ensure the estimation of environmental performance indicators on product level and express them in the appropriate measurement unit.
- The energy consumption fluctuation is also based on the type of products or group of products. Therefore, in the absence of actual data, energy consumption patterns should be kept for the different types of products.

- As the parameter of cost is very important, cost specificities regarding the production of products should be taken into account.
- Due to the various energy consumption fluctuations, there is a need of developing alerting mechanisms in order to control them or identify any technical problems.
- Due to the various factors that are responsible for energy consumption fluctuations (e.g. type of machines, type of articles), there is a need of modeling these various aspects of manufacturing (e.g. processes steps and articles) and conducting the environmental performance monitoring in a low level of detail.
- Time is the parameter used for the allocation of energy consumption of each machine to the various processes, order and articles. Therefore, there is intense time dependency of the various data needed in order to enable environmental performance monitoring e.g. detailed data in terms of time monitoring of the various processes steps are required in order to allocate the energy consumption of a specific period to these steps. Moreover, there is a need for tracking the workflow of various units e.g. processes, articles, orders

Warehouse and Distribution Context

We initially describe shortly the context under which the system was designed and implemented. Below, we discuss the specificities of warehousing and distribution. In general, the FMCG warehousing and distribution is characterized by diversities mainly driven by the great variety of transactions that take place, products and their dimensions, the routes traversed and the supply chain partners. It is not characterized by intense energy fluctuations such as manufacturing sector. Therefore, in comparison with manufacturing, we don't have many energy consumption fluctuations that are responsible for increased energy costs and should be moderated. The energy consumption fluctuations are mainly dependent by external conditions e.g. increased external temperature and can be affected by changes in the supply chain processes e.g. inventory management or distribution processes.

Below, we summarize the specificities in the supply chain that may affect the design and the implementation of the ECMS:

- The environmental impacts come from two different sources of consumption: the electrical energy and fuel consumption. The energy consumption is based on measured data that are provided either by energy monitoring infrastructures (e.g. sensors) or by energy suppliers. The fuel consumption data are either calculated by vehicle refills or are based on the industrial average values combined with transactional data such as distance travelled.
- The items (e.g. products/articles) that are monitored are final products. However, the same product could have various codes at the warehousing which increases the complexity of tracing a product even in warehousing level. The traceability of products is made more difficult when the scope is extended in the whole supply chain as the various partners have different codes for the same product. Therefore, a process that map the various available product data codes is essential in order to manage existing codes for the various entities and resources, ensure the estimation of environmental performance indicators on product level and express them in the appropriate measurement unit.
- The fuel consumption is differentiated based on the vehicle or vehicle type used at the different processes. Therefore, for each vehicle or type of vehicle information about fuel consumption should be kept. However, the energy consumption is not differentiated and energy consumption per sensitized objects e.g. energy power meters should be kept.

- The allocation of energy and fuel consumption to the product category and product level is based on the product weight or volume. Therefore, packaging details regarding product weight or volume are a prerequisite in order to enable environmental performance monitoring. However, this kind of information is inaccurate..
- More than one stakeholders are included which imposes the complexity of exchanging, synchronizing and integrating data is increased. Moreover, there is a need for tracking the workflow of various units e.g. processes, orders, and products across supply chain.
- In order to enable environmental performance monitoring the exact location of the facilities and the distances that a shipment covered should be known. Therefore, geographical considerations should be taken into account.

4 DESIGN AND DEVELOPMENT OF ENERGY AND CARBON MANAGEMENT SYSTEMS

4.1 Introduction

This chapter presents initially the need for developing energy and carbon management in the supply chain and defines its objectives and its various scopes. Then, a general set of design requirements that energy carbon management systems are suggested to cover and a general set of system components are derived. These components are incorporated in a conceptual high-level architectural framework that aims to specify in a more abstract level the components that this new class of information systems include. Even though the suggested architectural framework is context-independent and technology independent, contextual implementation settings may affect the design of these systems and lead to new requirements and system functionalities. Therefore, the chapter presents some of the contextual settings that may affect the design of such systems. We conclude by presenting a set of testable propositions that will guide their evaluation.

4.2 Purpose and Scope of Energy and Carbon Management Systems

Energy and Carbon Management in the supply chain is a domain that has attracted increasing interest over the last years. Monitoring and managing environmental impacts at the different stages of supply chain has been recognized as a main issue in the development of sustainable supply chains (Seuring & Müller, 2008). Building upon prior studies that discuss inefficiencies inherent in the conventional systems and working closely with practitioners in a real large-scale supply chain context, we identified numerous purposes for managing the energy and carbon information and monitoring the environmental impacts of a firm. Two key purposes for valuing and improving the environmental impacts are:

- **Reduce cost and mitigate operational improvements:** companies wish to control the energy consumption and carbon emissions in order to reduce both the cost as well as the dependence on non-renewable sources and make better managerial decisions.
- **Respond to regulatory and consumer demands:** companies have to account for their energy consumption and carbon emissions both to regulatory forces (that are expected to increase in the future) and to consumers, whose environmental consciousness is in the rise.

Such a monitoring forms the basis for controlling the energy consumption and carbon emissions of supply chain processes, for making environmental-aware decisions regarding improvement measures and for tracking the progress in the energy consumption and carbon emissions. Thus, a growing number of firms integrate carbon footprint monitoring in the management of their supply chain (Lee, 2011; Sundarakani, 2010). However, managing individual indicators, such as energy consumption and carbon emissions, within the supply chain context is not straightforward and it is cost and time-consuming. Single and aggregated measurements can satisfy to some extent the key requirement of regulatory and consumer demands, but cannot deliver operational improvements and bring light to strategic prospects. To make better managerial decisions, it is important to accommodate a broader spectrum of energy and carbon information. With that in mind, an ECMS should support multiple “views” that allow a diverse and flexible use of energy and carbon monitoring.

To meet this purpose, the scope of an ECMS in the supply chain context should include different dimensions of monitoring, reporting and decision support. Firstly, Energy and carbon management in the supply chain should address all players (Ahi & Searcy, 2014). Therefore, its scope extends from the supplier that provides a firm with the raw materials up to the point of sales where customers buy the final products (Fig 4.1). This scope includes three main activities: manufacturing, warehousing and transport (The Consumer Good Forum, 2012). According to the Consumer Good Forum (2012), the warehousing includes warehousing activities related to the storage and handling of raw and packaging material at source or semi-finished or finished goods at the regional or local destination markets. It could be executed in-house, as well as outsourced to logistics service providers. The transport includes inbound and outbound transportation activities across all transportation modes (e.g. road, rail, sea, inland waterways, and multimodal transportation). It could be a transportation planned, controlled and executed in-house, as well as outsourced to logistics service providers. Manufacturing activities includes activities related to the production of raw materials, semi-finished or finished goods energy and carbon management for manufacturing is recommended to be handled separately, as this allows for analysis and details focused on manufacturing specifics (The Consumer Good Forum, 2012).

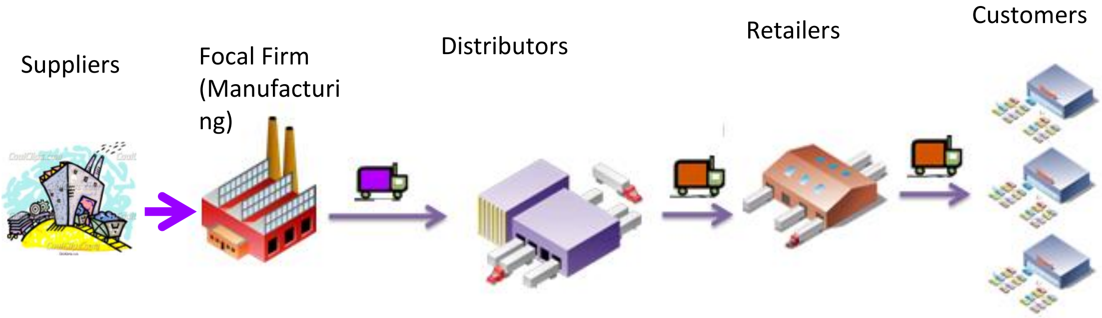

Figure 4.1: The scope of Energy and Carbon Management

As supply chains may be viewed as being comprised of manufacturing nodes, logistics nodes and links, we should also propose a supply chain hierarchy that will be used to allow estimating metrics at a gross level and delve down to finer levels when needed due to importance of certain nodes and links or specific interest in some nodes and links. The idea of successively looking at more detailed level is similar to the idea of layers of supply chain used by Sarkis (2012) and Jain et al., (2013). Moreover, there is also the need of associating environmental aspects to traditional supply chain and manufacturing aspects, e.g. associating energy and carbon emissions indicators to warehousing capacity utilization. Therefore, collecting and integrating various types of information from different existing systems (such as ERP, warehouse management systems, energy sensors, building management systems etc.) is required. For the data collection to take place, we should firstly define the sensitized objects that refer to "a physical good that has the capability to sense and report data about its use" (Watson et al., 2010) and defines the main source of environmental data. An example of sensitized object could be a machine or a vehicle and it usually refers to the lower level of analysis for energy and carbon management.

Based on our extensive interaction with the Industrial Interest Group and the four organizations, we define the purpose and scope of energy and carbon management, the respective supply chain hierarchy levels and sensitized objects for each scope. We conclude that the scope and purpose of energy and carbon management should include four different dimensions of monitoring, reporting and decision support:

- **Managing energy consumption and carbon information for manufacturing.** An ECMS would account for tracking energy consumption and quantifying potential savings related to manufacturing processes of the supply chain and improving their environmental impact. In this context, the sensitized objects are the production machines that are responsible for the greatest part of energy consumption. However, energy consumed by activities (e.g., lighting, cooling/heating and ventilation) that are not involved directly in products' manufacturing, known as indirect energy, would be taken into account. In manufacturing, a broad division of energy and carbon management is suggested and is divided into three levels referred to managing energy consumption and carbon information at process level, managing energy consumption and carbon information across processes, managing energy consumption and carbon information at an aggregated level (see Section 3.4.2). Except from the energy and carbon related indicators, traditional manufacturing indicators such as total idle time for selected machines or process steps, makespan, Quantity produced (in Kg, m) per article and associate environmental performance to utilization indexes. Moreover, the calculations of these indicators would be conducted at different ‘granularity’ levels, e.g. per machine step, machine etc (see Table 4.1). To support both monitoring and advanced decision-making capabilities, an ECMS should receive energy consumption and operational data related to each node/section either by energy sensors or by ERP/WMS and legacy systems.
- **Managing energy and carbon information for warehousing.** An ECMS would account for tracking energy consumption and quantifying potential savings related to specific nodes/sections of the supply chain (e.g. per store/warehouse) and energy-greedy infrastructures (e.g. per fridges, lighting etc.). In this context, the sensitized objects are the warehouse/store power supplies. Except from the energy and carbon related indicators, traditional warehousing indicators such as inventory levels would be measured and associated to energy and carbon ones providing a more integrated view. Moreover, the calculations of these indicators would be conducted at different ‘granularity’ levels, e.g. per facility, per store/warehouse, per section, such as refrigeration etc (see Table 4.1). To support both monitoring and advanced decision-making capabilities, an ECMS should receive energy consumption and operational data related to each node/section either by energy sensors or by ERP/WMS and legacy systems.
- **Managing energy and carbon information for distribution activities.** An ECMS would account for tracking energy consumption, controlling and improving environmental impacts of distribution processes, e.g. per vehicle, per distribution link, per route. In this context, the sensitized objects are the vehicles and their fuel consumption. Except from the energy and carbon related indicators, traditional distribution indicators such as vehicle fill rate, distance travelled, weight distributed would be measured and associated to energy and carbon ones providing an more integrated view. Moreover, the calculations of these indicators would be conducted at different ‘granularity’ levels, e.g. per facility, per store/warehouse, per section, such as refrigeration etc (see Table 4.1). The informational value is depending on collecting fuel data from various data sources (e.g., refills) and integrating them with traditional supply chain indicators such as vehicle fill rate, distance travelled, weight distributed.
- **Managing energy and carbon information across the supply chain**. An ECMS would track the energy consumption across the supply chain (e.g. 3PLs, warehousing providers, retailers, suppliers) and identify problematic areas. It combines the two previous views

(warehousing/distribution). It will also provide the basis upon input support the development of decision support tools to support operations and supply chain management and design decisions, taking into account environmental KPI's and the dynamic energy profile of products and processes. To do so, the design of such a system should incorporate energy and operational data per individual node as well as data related to the movement of products across the supply chain. As such, an ECMS presupposes the collection of data from different nodes in the supply chain and even the data exchange with supply chain partners.

The following table summarizes the energy and carbon management scopes and their respective supply chain hierarchy levels. At this point we should also stress the importance of managing energy and carbon information at product level due to regulatory requirements and consumer concerns. An ECMS should not only monitor and measure energy consumption and carbon footprint but also support the allocation of total carbon consumed during the whole life cycle to each item. Hence, such a system should take into account the need for a per-item environmental profile, including energy consumed and the CO_2 equivalent emitted throughout its life cycle.

Table 4.1: Energy and Carbon Management Supply Chain Hierarchy

Manufacturing	**Warehousing**	**Distribution**	Supply Chain
Machine	Store/warehouse section	Vehicle	Store/warehouse
Process step	Store/warehouse	Distribution link	Vehicle
Process	Product category and product	Route	Distribution link
Production order		Distribution networks	Route
Department		Product category and product	Supply chain networks
Facility			Product category and product
Article			Store/warehouse section

One of the key issues in the energy and carbon management is the specification and the definition of the performance indicators that will be monitored. The type of indicators in terms of system design is critical in order to define the data related requirements and their granularity (in terms of time and level of analysis) and also guide the deployment of the respective calculation logic. We have identified three different types of KPIs: the environmental that refer to energy consumption and carbon emissions, the operational that refer to the performance of supply chain processes and the integrated that combine the environmental and the operational view.

As our study aims to contribute to the design of an ECMS focusing on supply chain settings, a comprehensive and flexible blueprint of how information is organized determines the success of the designed artifact (Hicks et al., 2002). In such a vision, the design of an ECMS to support energy and carbon insight and intelligence has one key aspect to be addressed: the structure and management of the information. Based on this vision, all information needed to support an ECMS goes beyond a single view and is presented in different forms in order to cover each scope specificities and also include various aspects such as time, product, physical unit (e.g. store, warehouse, vehicle, shipment, production order, machine), the source is required. Thus, it is imperative to 'bridge' the divide that separates all information. The aforementioned goal imposes the need for collecting and integrating various types of information from different existing systems (such as ERP, warehouse management systems, energy sensors, building management systems etc.) in order to support each one of the aforementioned managing dimensions. Despite the heterogeneity of the various data, they could be classified into the following information flows:

- **Contextual information flow (CI)**: this includes information regarding the products, facilities, supply chain partnerships and supports the interpretability of the transactional information.
- **Transactional information flow (TI)**: this includes information regarding the transactions that take place in the supply chain such as ordering, distributions, inventory management.
- **Environmental information flow (EC)**: this includes information regarding energy consumption that is either measured by energy sensors or retrieved by existing Building Management Systems. It also includes fuel consumption information referring usually to vehicle fuel refills or to actual fuel consumption monitored through sensors and metering devices installed on vehicles.
- **Product environmental information flow (PEIF)**: this includes information on the environmental profile of the products, as provided by external sources, including the embodied carbon footprint of the products as recorded by other partners or Life Cycle Inventories (LCI).

The above information flows could be an initial point in order to proceed with a more detailed data specification process and also to identify the data sources. For example, production information related to machines and their mapping to processes (handled by applications such as Manufacturing Execution Systems (MES) and Advanced Planning and Scheduling (APS); product information (stored in applications such as Product Data Management (PDM) or ERP); business information related to the orders, articles and quantities to be produced, stocks of raw materials (processed by applications such as ERP or Supply Chain Executions Systems); energy and carbon emissions information (captured by sensors, Life Cycle Inventories-LCI etc.), assets information (stored in ERP or WMS), inventory and delivery information (stored in ERP or WMS). Therefore, the information needed to support the managing presents itself in different forms and may thus be "isolated" in distinct data warehouses and systems.

4.3 Design Requirements and Justificatory Knowledge

Having defined the purpose and scope of Energy and Carbon Management, we proceed by deriving a set of design requirements from justificatory knowledge, including both literature and practitioners insight, that give guidance to the subsequent specification of our design.

In responding to increased sustainability challenges, information systems are recognized as a key resource to support organization in sustainability transformations (Seidel et al., 2013; Thibodeau, 2007). More specifically, information systems impact the enablement of sustainability transformations in terms of organizational sensemaking and sustainable work practices implementation (Seidel et al., 2013). They support that information systems could afford possibilities for cognitive activities through which individuals across the entire organization could frame, interpret, and understand the multilayered and complex issues related to the environmental sustainability transformation (Seidel et al., 2013). In this context, information systems are called to handle the growing demand for alternative, previous inconsiderable, increasingly multidisciplinary and interrelated information from both internal and external sources (Choo, 2006; Elliot, 2011; Pitt et al.,2011; Seidel et al., 2013) and to develop information-based capabilities (Kohli & Melville, 2009).

Seidel et al., (2013) pose that the required organizational sensemaking process was enabled through functional affordances of reflective disclosure and information democratization, which enabled the identification, provision, analysis, and interpretation of multilayered information pertaining to the new sustainability theme. More specifically, reflective disclosure refers to these system features that allow monitoring, analyzing, and presenting information regarding current work practices in relation to environmental impact data and of relevant new performance indicators (technology) (Seidel et al., 2013). Information democratization refers to the system features that allow diffusion of information about the sustainability theme together with mechanisms to personalize, comment, feedback, and propagate.

Based on the above, we pose that ECMS should support firms to standardize, monitor, capture, utilize and interpret data and metadata and to diffusion of information in order to enable energy and carbon management. For example, an ECMS should collect and store the information gathered by sensor networks and sensitized objects and analyze these information to organizational stakeholders (Watson et al., 2010). Due to the information-intensive nature of Energy and Carbon Management, many researchers highlight the need for the integration of information flows (Bunse et al., 2011; Vikhorev et al., 2013; Watson et al., 2010; Rünger et al., 2011). Therefore, the design of an IS is highly dependent on "gluing" together various data sources with which it shares information and elaborating on the effective integration of the various information flows would be an initial point of ECMS design. In order to supporting stakeholders to interpret the collected information and assessing current work practices, the information collected should be transformed in environmental key performance indicators (e.g. carbon footprint, total energy consumption, renewable energy consumption, etc) that provides an integrated view both operational and environmental ones (Groot et al., 2001; Veleva & Ellenbecker, 2001). Therefore, new Key Performance Indicators that support an integrated sustainable view should be defined and incorporated in an ECMS (Petrini & Pozzebon, 2009).

Aided by the energy and carbon management process described above, information systems also contributes to the establishment of environmentally sustainable work practices (Bengtsson & Ågerfalk, 2011; Dao et al., 201*1*; Seidel et al., 2013) and to environmental-aware decision making (Butler, 2011). Therefore, ECMS could be able to cover the aforementioned challenges by incorporating e.g. features that range from comparison and aggregation features, visualization and even automation mechanisms for suggesting solutions for energy consumption and carbon emissions reductions.

Even though the design of ECMS aims to be context-independent and technology-independent, contextual implementation settings may affect the design of this system. For example, the scope of supply chain (Manufacturing, Warehousing, Distribution and across supply chain) imposes different requirements as it is related with different processes of the supply chain. Therefore, different kinds of data are needed in each scope and in the case of across supply chain information sharing is required. Moreover, the reasons behind an ECMS implementation may affect its design for example different Key Performance Indicators should be included when the energy cost reduction by optimizing production processes is the main goal or when annual carbon reporting is the objective. In the second case aggregated energy consumption data even on annually level could be used.

Some of the most prominent issues in the implementation of ECMS in the supply chain, that the exploratory research and the literature review revealed, are related to the following aspects: a) Data quality and availability, b) Data capture and integration, c) Environmental

Performance Metrics selection and d) Collaboration and Information Sharing. The system would have the ability to tackle these issues and the design should take them into account. According to ISDT terminology presented above, this is called artifact mutability and refers the changes that affect the basic form or shape of the artifact and allows for a certain amount of adaptation or evolution to the implementation context.

By taking into account the above and also practitioners insights (more details on Section 3), following generic requirements, we conclude to a set of generic design requirements. They were identified and summarized in Table 4.2. Our aim is not to present the exhaustive set of Design Requirements for Energy and Carbon Management Systems design, but rather to first outline some essential requirements for these systems and to demonstrate the applicability of design theory.

Table 4.2: Energy and Carbon Management Systems Design Requirements

Requirements	**Explanation**
Energy and fuel consumption data collection	Energy consumption from energy meters needs to be collected, the energy streams needs to be handled and alerting mechanisms needs to be supported where applicable for enhancing energy and carbon efficiency.
Operational data collection	Information about transactions (production processes, distribution process) and contextual information e.g. regarding the machines, processes, products, inventories deliveries, partnerships needs to be collected.
Energy consumption data collection from non-sensor resources	The management and utilization of energy consumption flows non-recorded by sensors needs to be supported. Such flows include for example the information coming from energy audits, as translated into energy vectors or energy consumption bills or fuel refills.
Environmental impacts estimation	A business logic that will enable the calculation of carbon emissions and the allocation of environmental impacts on more detailed level of analysis, e.g. process, product etc. needs to be implemented.
Workflow monitoring	The monitoring and the supervision of the various supply chain processes needs to be supported.
Environmental reporting	The required Key Performance Indicators needs to be presented in various formats.
Supply chain modelling	The design and modelling of the various supply chain processes and networks needs to be supported
Information exchange	Information sharing, information synchronisation and the collaboration with supply chain partners needs to be supported.
Integration Support	Various interfaces needs to be provided for ensuring the integration with the existing systems
Intraorganizational collaboration and coordination	The coordination of the processes and the data received from the various supply chain partners needs to be supported.

As discussed above, the specification and the definition of the performance indicators that will be monitored is one of the key issues in the Energy and Carbon Management design. There are various indicators that cover aspects such as the scope of supply chain (manufacturing), the type of indicator (environmental, operational, integrated), the level of analysis. The complexity of calculations imposes the need of calculating more complex KPI_S and allocating the environmental impacts at different levels of analysis. Moreover, various environmental standards should be supported and an interface for parameterizing the allocation logic should be enabled.

Based on the above, we identify two extra requirements

Table 4.3: Energy and Carbon Management System Requirements related to KPIs

Requirements	**Explanation**
Estimating KPIs	A business logic that will enable the calculation of the required Key Performance Indicators needs to be implemented
Configuring KPIs Calculation Logic	The ability to configure the KPIs calculation logic parameters needs to be provided.
Defining New KPIs	The definition of new Key Performance Indicators needs to be supported.

In Section 4.2, we discussed the need of collecting and integrating various types of information from different existing systems (such as ERP, warehouse management systems, energy sensors, building management systems etc.) in order to support each one of the identified managing dimensions. We have also identified four main information flows: contextual information flow, transactional information flow, environmental information flow and product environmental information flow. The information needed presents itself in different forms, e.g. production information related to machines and their mapping to processes), product information, business information related to the orders Each such information serves a different scope and may thus be "isolated" in distinct data warehouses.

In this context, data quality and availability and data and data capture and integration is a critical issue. For example, environmental data are either completely absent or merely available at high aggregation levels. Therefore, ECMS have to tackle various issues related to limited data availability, data synchronization, and different levels of data granularity, data integration and the automation of the data acquisition process. Following the approach presented above, we conclude on a set of generic requirements, summarized in Table 4.4.

Table 4.4: Energy and Carbon Management Systems Design Requirements related to data

Requirements	Explanation
Data validation	Validate and cleansing-up the data received is needed in order to the date to be integrative.
Data specification compliance	The received data is needed to be compliant to the data specification standard for the ECMS.
Automated input interfaces	Automated input interfaces are required in order to enable the collection of environmental and operational data from existent business information systems automatically.
Provision of quality indices regarding data availability	The data availability needs to be examined and the respective indices related to it needs to be provided.
Ensuring the same level of granularity	The data received is needed to have the same level of granularity e.g. inventories from all warehouses and stores should be stored on a daily basis.
Data transparency	Information about data type and origin as well as collection proofs regarding the environmental and operational data e.g. secondary environmental data are used for the estimations should be provided
Data synchronization and mapping	Mapping the entities and synchronizing the data received from other resources e.g. map the codes for products from different suppliers is needed.

While economic and operational data are available in existing systems, various integration issues regarding information technology remain to be tackled before incorporating both environmental and non-environmental aspects. Achieving energy and carbon management in the supply chain demands the integration with external resources. To better illustrate the requirement of the integration with existing systems (e.g. ERP, WMS, BMS, LCI), we have identified the main systems with which ECMS interacts. Table 4.5 gives a short description for each system.

Table 4.5: Systems Description

External Systems	Description
Enterprise Resource Planning (ERP)	The system that a company can use to collect, store, manage and interpret data from many business activities, including: product planning, cost, manufacturing or service delivery, marketing and sales, inventory management, shipping and payment. It provides information regarding e.g. for production orders, inventories, invoices.
Warehouse Management System (WMS)	It aims to control the movement and storage of materials within a warehouse and process the associated transactions, including shipping, receiving, put away and picking. It provides information regarding e.g. deliveries and inventories.
Building Management System (BMS)	A system that controls and monitors the building's mechanical and electrical equipment such as ventilation, lighting, power systems, fire systems, and security systems This system is responsible for measuring energy consumption that will be utilized in order to support monitoring in warehouse and store level.
Energy Sensors	These sensors monitor energy consumption at the specified levels and will feed the ECMS with the respective energy consumption data.
Manufacturing Execution Systems	Manufacturing Execution System (MES) is a control system for managing and monitoring work-in-process on a factory floor. This will provide the required information regarding the manufacturing production processes.
LCI Repositories	They provide individual gate-to-gate, cradle-to-gate and cradle-to-grave accounting of the energy and material flows into and out of the environment that are associated with producing a material, component, or assembly.

Above we have presented a set of design requirements as they come by following the process described in Section 3. ECMS is expected to contribute to the implementation of environmentally sustainable supply chains by supporting energy and carbon management, environmental-aware decision making and the implementation of environmentally sustainable supply chain practices. Therefore, we want to explore if the proposed design supports the above and we formulate the following three testable propositions.

Testable Proposition 1: How does an energy and carbon management system following the proposed design supports energy and carbon management in the supply chain?

Testable Proposition 2: How does an energy and carbon management system following the proposed design supports environmental - aware decision-making in the supply chain?

Testable Proposition 3: How does an energy and carbon management system following the proposed design supports the implementation of sustainable supply chain practices?

4.4 A Conceptual Architectural Framework for Energy and Carbon Management Systems

In order to cover the design requirements, as presented above, we proceed by tracing a set of general components that should be included in an ECMS. Special emphasis has been given on the integration of the various information flows as it is prerequisite for most of the requirements presented before and should be addressed by most of the components. Let us now propose a set of mandatory components that cover the requirements related to both manufacturing and supply chain by integrating the respective information flows (Fig. 5.1). The relation of the components and the aforementioned design requirements is presented in detail in Appendix C.

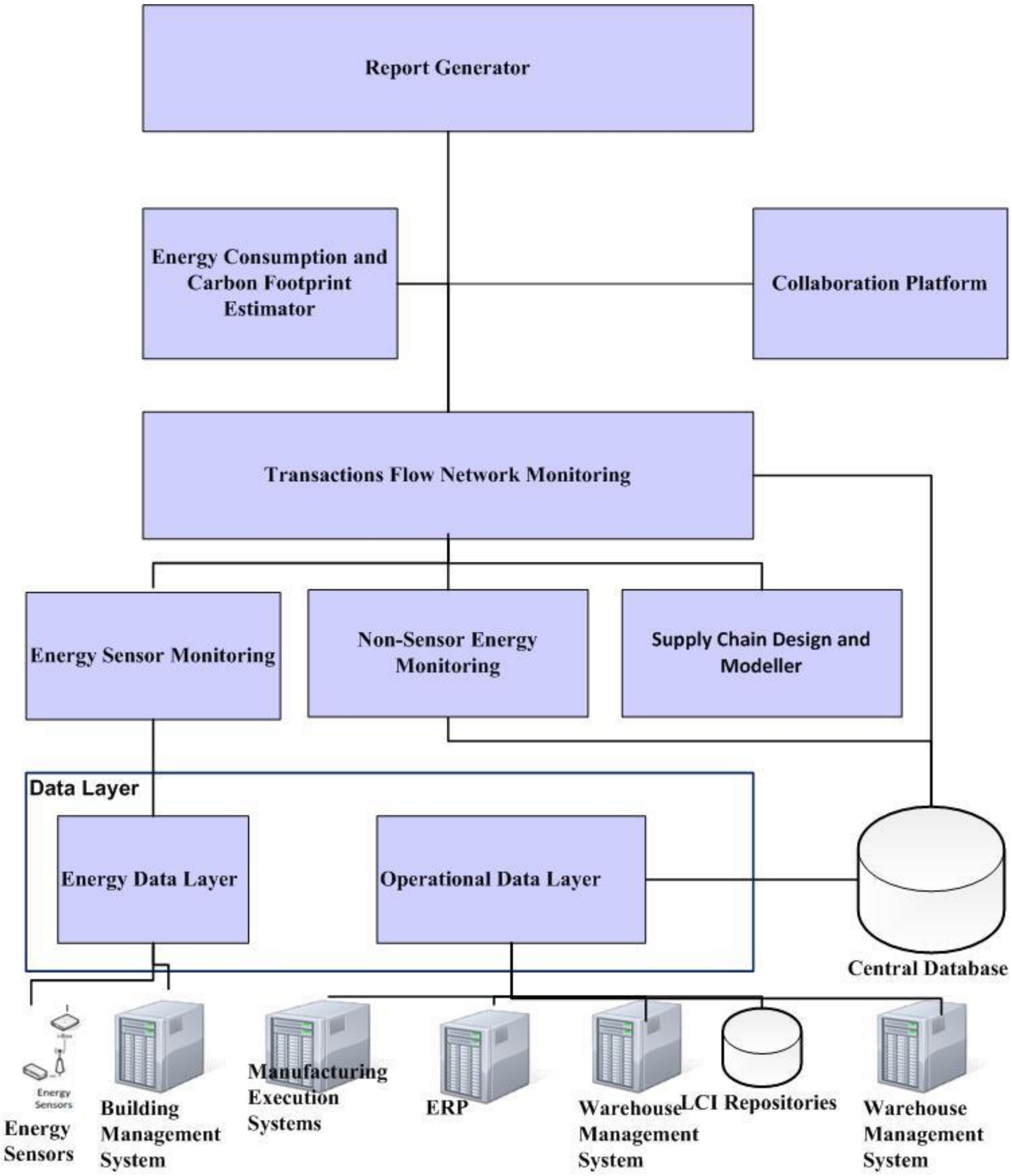

Figure 4.2: Architectural Framework for Energy and Carbon Management System

Here are the components and their primary functional objectives.

- The **Data Layer** refers to the main data interface that acts as a single receiver of all available data sources. As energy and carbon management is a data-intensive procedure, it requires transactional and contextual data from various sources. Therefore, a component that collects, validates, cleans-up and identifies the relations among them becomes crucial. This component consists of two separate sub-components that function independently of one another: the Energy Data Layer, and the Operational Data Layer. The former orchestrates the communication and synchronization with energy sensors and Building Managements Systems thus receiving and storing all energy consumption data, while the latter imports data from existing systems such as MES, ERP, WMS. Thus, this component handles all the transactional and contextual information required to monitor supply chain activities.
- The **Energy Sensor Monitoring** collects energy consumption data from the Energy Data Layer and implement a business logic for aggregating energy consumption at different levels of analysis and combining the energy data with the infrastructural information, e.g. it calculates the energy consumption per department of a manufacturing site. In terms of information flows, this component handles the environmental information flow and the contextual information flow (specifically associating energy power meters and products to specific warehouse and store sections).
- The **Non-sensor Energy Monitoring** utilizes all energy consumption flows non-recorded by sensors, e.g., the energy consumption recorded by energy bills. Such flows include the information coming from energy audits in the manufacturing cases, as translated into the energy vectors needed e.g. for calculating indirect energy in the manufacturing case. In terms of information flows, this component handles the environmental information flow and the contextual information flow (specifically associating energy power meters and products to specific warehouse and store sections).
- The **Supply Chain Design and Modeler** has the objective of modeling and designing the supply chain and providing all the required information regarding the supply chain objects of interest (e.g. processes, node, product details, partners details, geographical information etc.). This component partially models the enterprise structure in order to maintain and disseminate semantic information regarding the organization’s underlying structure (e.g. facilities, departments), the production arrangement (e.g. processes and process steps), the composition of an article / piece etc. Since supporting energy and carbon management requires the structure of the supply chain and the scope of monitoring to be defined, this component supports the definition of the scope based on a user's existing supply chain settings. In terms of information flows, this component handles the contextual information flow.
- The **Transactions Flow Network Monitoring** refers to the monitoring and supervision of a set of processes, e.g. distribution, ordering or production. This component is responsible for (a) monitoring the daily activities (shipments, storage, production) and (b) supporting the calculation of the required KPI’s for the different levels of analysis. This component tracks all supply chain processes and initiates the procedure of estimating energy and carbon footprints. Also, it communicates with the collaboration platform to receive/submit information from supply chain partners. In terms of information flows, this element handles the environmental information flow, transactional information flow, contextual information flow, environmental information flow and product environmental information flow, as it is a central component of the proposed architecture.
- The **Energy Consumption and Carbon Footprint Estimator** includes the business logic for aggregating and disaggregating anticipated energy consumption, transforming them into

carbon emissions and then estimating the carbon footprint, using allocation methodologies such as LCA. Specifically, it computes the carbon emissions of the activities (processes) of manufacturing, warehousing, distribution (emissions from warehouses, stores, transportation and packaging materials), at all levels listed in Table 4.1. Since the calculation and allocation of environmental impacts is a complex procedure, often based on various methodologies, this component allows the user to review and set the allocation parameters of that procedure. as the information regarding the distribution process were not available at the required level of detail. This element mainly handles the environmental information flow, but receives as input both contextual and transactional information.

- The **Report Generator** creates standard formatted reports that cover all the aspects of energy and carbon management in the supply chain (e.g. energy measurement, carbon footprint at different levels of analysis etc.). A dedicated reporting component is important in order for a user to perceive the system as one homogeneous entity and understand the systems' value.
- The **Collaboration Platform** refers to the component that is responsible for maintaining the collaborative relationships among the supply chain partners and facilitating data exchange. Most importantly, it provides data to other components from different partners. Although non-surprising, this component enables the supply-chain-wide scope of the overall architecture. Therefore, an independent component that supports it is needed. In terms of information flows it handles all types of information flows that come from external partners.

Notice that our framework could also include a component for sensors measuring actual fuel consumption or a component for non-sensor fuel consumption monitoring. However, based on our cases and the current state of the art, fuel consumption data are usually not available. Therefore, the estimations of fuel consumption and the respective carbon emissions are based on industrial vehicle-related fuel consumption averages, that are usually incorporated as parameters in the Energy Consumption and Carbon Footprint Estimator.

5 EVIDENCE FROM DEMONSTRATION AND EVALUATION IN MANUFACTURING

5.1 Introduction

The aim of this chapter is to present how the Energy and Carbon Management System artifact has been designed, developed and deployed in the two cases studies in the manufacturing. Having as starting point the outcome of Section 4, we elucidate them in the context of manufacturing by capturing and presenting more precise system requirements, data requirements and KPIs. Then, we specify the components that incorporate these requirements, the architecture of the artifact, the design principles for each system component and provide an artifact instantiation. Then, we describe the exact real-case settings under which we implemented the two systems and the implementation process. The step of evaluation is conducted in two phases, so that the first phase could give feedback to the second round of design and development. The first round revealed a set of challenges imposed e.g. by the limited environmental data availability. Evidently, these challenges reveal specific design and implementation principles to be implemented in order to ensure the efficacy of such systems in a real-world context. We conclude by providing evidence regarding the impact of these systems on the enablement of environmental sustainable supply chains and more specifically energy and carbon efficient manufacturing by supporting energy and carbon management, environmental-aware decision-making and sustainable supply chain practices implementation.

As discussed in Section 4.2, Energy and Carbon Management for manufacturing is recommended to be handled separately from warehousing and transportation, as this allows for analysis and details focused on manufacturing specifics. Therefore, we present below the evidence from manufacturing cases.

5.2 Energy and Carbon Management System Design and Development in Manufacturing

Within the context of this study (see 3.4.2 for Manufacturing Specificities), Energy and Carbon Management consists of three scopes, as depicted in **Error! Reference source not ound.**5.1. The first level refers to Energy and Carbon Management at the process level, i.e., it considers machines and process steps (i.e., the non-divisible steps in production) whose energy consumption is being metered and monitored. The second level refers to direct and indirect energy consumption monitoring and covers inter-process and inter-department management, thus relying on the first level. Traditionally, a department shows the functional units of the factory; however, here, department is defined as an area within the manufacturing plant with a similarity of processes (e.g. a machining cell) or products (e.g. a production line) to be monitored. The third level refers to a more aggregated level (such as the manufacturing of an article, a future production order) and, as a result, the values of energy consumed are not real measurements but estimations (e.g., averages).

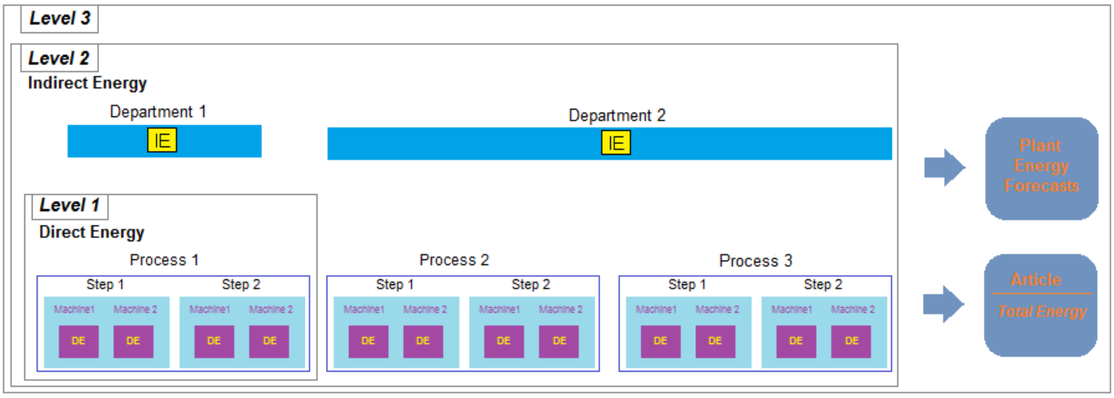

Figure 5.1: Three levels of Energy and Carbon Management in Manufacturing

We describe each one of the levels below:

- **Managing energy consumption and carbon information at process level**. The objective of this level is to provide the basic functionality regarding the measurement of real energy consumption and carbon within each process step and/or machine. It also supports the association of energy measurement with production data. Note that this level examines only direct energy consumption, i.e., the energy associated directly with the operation of a machine or group of machines (and not, for example, heating or air-conditioning that are indirect energy sources). Therefore, this level bridges the gap between the measurement of actual consumption and the production sequence.

- **Managing energy consumption and carbon information across processes**. This level extends the previous one and monitors direct energy consumption and carbon across different processes, while also allocating indirect energy consumption to articles (i.e. items produced in a sequence of processes within possibly non-identical production orders).

- **Managing energy consumption and carbon information at an aggregated level**. This level extends the previous ones and monitors energy consumption and carbon at an aggregated level (per article or/and per order), shifting its functionality from measuring to estimating. That is, this level offers estimated/planned values of energy consumption (and not measured) per process or per order and is based on historical data obtained by the previous levels or based on energy vectors. In addition, it validates the estimations either by comparing them to real data or by receiving feedback from the users.

One of the key issues in the energy and carbon management is the specification and the definition of the performance indicators that will be monitored. The type of indicators in terms of system design is critical in order to define the data related requirements and their granularity (in terms of time and level of analysis) and also guide the deployment of the respective calculation logic. We have identified above three different levels of energy and carbon management in the scope of manufacturing and the respective level of analysis. However, we should expand each one of them by identifying a set of KPIs. The Key Performance Indicators that were developed take into account the following aspects: the type of indicator (environmental, operational, and integrated) and the level of analysis as (presented in Table 5.1) and the measuring unit. The KPIs identified are limited as the objective is not to define an exhaustive list of KPIs that would serve business goals but to identify a series of challenges that would affect the design and the implementation of Energy and Carbon Management System and to provide a proof-of -concept.

Below we present the various level of analysis and the key performance indicators based on the aforementioned aspects.

Table 5.1: Level of analysis in Warehousing and Distribution

Level of analysis
Machine
Process step
Process
Production order
Facility
Article

Table 5.2: Key Performance Indicators in Manufacturing

Indicator	Type	Level of Analysis	Measuring Unit
Total Energy consumption	E	Machine, Process step, Process, Production order, Facility, Department ,Article	KWh
Total Indirect Energy Consumption	E	Machine, Process step, Process, Production order, Facility, Department, Article	KWh
Total CO2e emissions	E	Machine, Process step, Process, Production order, Facility, Department, Article	kg
Total Energy Costs	O	Machine, Process step, Process, Production order, Facility, Department, Article	Euro
Number of products produced	O	Machine, Process step, Process, Production order, Facility, Article	items, pallets, tone, kg
Machine Idle Time	O	Machine, Process step, Process, Production order, Facility	mins
Makespan	O	Machine, Process step, Process, Production order, Facility	mins
Energy efficiency	I	Machine, Process step, Process, Production order, Facility, Department, Article	KWh/reference unit of the level of analysis
CO^2 efficiency	I	Machine, Process step, Process, Production order, Facility, Department, Article	Kg/reference unit of the level of analysis

In order to support the energy and carbon management level and the calculation of the various KPIs, we have identified the data entities and the respective data flows that are required. The data entities were classified in the following categories of information flows: Transactional information flow (TI), Contextual information flow (CI), Environmental information flow (EC), Product environmental information flow (PEIF). Figure 1 (Appendix D) depicts data entities along with their respective flows in a unified data model. Additionally, a description of these entities appears in Table 1 (Appendix D). The data model and the table present the minimum required list of data entities that are required in order to support the three levels that have been defined in manufacturing. Almost the extensive data set is required in order to support each level of management in the manufacturing (Table 5.3). The integration of all information flows is required in all cases.

Table 5.3: Data requirements per Energy and Carbon Management Level in Manufacturing

Data Entity	Managing energy consumption and carbon information at Process Level	Managing energy consumption and carbon information across Processes	Managing energy consumption and carbon information at an aggregated level
Article	√	√	√
ReferenceUnit	√	√	√
Department	√	√	√
Facility	√	√	√
Partner	√	√	√
BoM	√	√	√
Machine	√	√	√
Process Step	√	√	√
Process	√	√	√
ProductionPhase	√	√	√
Sensor	√	√	√
MeasuringUnit	√	√	√
OrderedArticle	√	√	√
Order	√	√	√
ArticleTracking	√	√	√
ArticleStepSequence	√	√	√
Resource	√	√	√
ResourceConsumption	√	√	√
ResourceVector		√	√
IndirectResourceConsumption		√	√
Material			√

The distributed and heterogeneous environment in which ECMS operate imposes the need of using technologies that support componentization and can improve the reusability and integration of the systems such as, object-oriented design, web services, eXtensible Markup Language (XML), and service-oriented architecture. Based on the above, the architecture of the artifact is designed. The system architecture is depicted in Figure 5.2 and shows a logical decomposition of the system's components that will interact in order to support the desired Energy and Carbon management levels. Last but not least, an ECMS needs to meet some non-functional requirements (see Appendix F). The non-functional requirements have been collected from the input and the discussion with the business partners and were based on the Standard ISO/IEC model, which defines quality standards by identifying a set of features and attributes that a generic software needs to have.

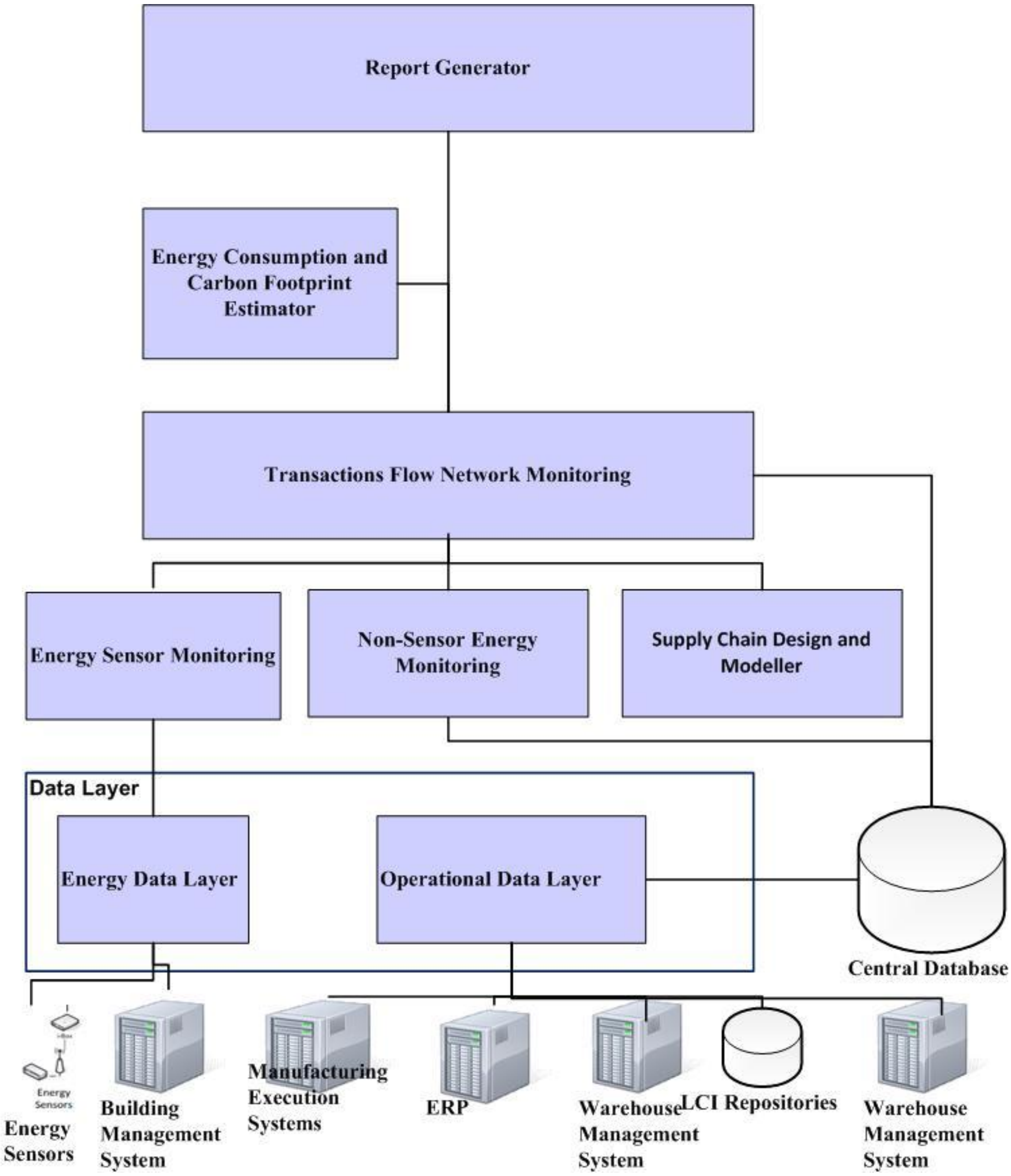

Figure 5.2: Architecture of the Energy and Carbon Management System Instantiation in Manufacturing

For brevity reasons, we present below only the list of the resulting components and their primary functional objectives. The detailed list of each component design principles is presented in Appendix E (Table E.1):

- The **Data Layer** refers to the main data interface that abstracts and simplifies access to data stored in persistent storage, providing a common interface for the native data base operations, leaving the rest of the application agnostic to the underlying data storage infrastructure. Energy and Carbon Management is a data demanding process, which requires transactional and contextual data from various sources. Therefore, a component that collects, validates, cleans-up and identifies the relations among them is crucial for such an infrastructure. This component consists of two separate sub-components that will function independently of one another: the Data Layer energy sub-component, and the Data Layer Manufacturing sub-component. The first handles the communication and synchronization with energy sensors and Building Managements Systems, while the second Operational Data Layer imports data coming from ERP, WMS, MES and other corporate systems. Thus, this component handles all the transactional and contextual information required to monitor manufacturing activities.

- The **Energy Sensor Monitoring** has the objective of collecting energy consumption data from the Energy Data Layer and implement a business logic for aggregating energy consumption at different levels of analysis and combining the energy data with the infrastructural information e.g. energy consumption per machine. This component ensures the required energy consumption data will be available and covers in that way one of the prerequisites for the successful implementation of the industrial requirements. It manages the underlying data infrastructure that will supply (automatically or semi-automatically) the energy data stream consumed during product's production. It should be capable either to support a proprietary sensor's infrastructure or manage a sensors network. In terms of information flows, this component handles the environmental information flow and the contextual information flow (specifically associating energy power meters and products to specific machines, processes and articles).
- The **Non-sensor Energy Monitoring** utilizes all energy consumption flows non-recorded by sensors, e.g., the energy consumption recorded by energy bills. Such flows include the information coming from energy audits in the manufacturing cases, as translated into the energy vectors needed e.g. for calculating indirect energy. In terms of information flows, this component handles the environmental information flow and the contextual information flow (specifically associating energy consumption to specific processes).
- The **Supply Chain Design and Modeler** has the objective of modeling the enterprise structure in order to maintain and disseminate semantic information regarding the organization's underlying structure (e.g. facilities, departments), the production arrangement (e.g. processes and process steps), the composition of an article/piece etc. The functionality that will offer needs to be flexible in order to meet different enterprise settings. As contextual information is critical for the successful implementation of energy and carbon management, this component also presents this information and lets the user update it. In terms of information flows, this component handles the contextual information flow.
- The **Transactions Flow Network Monitoring** refers to the supervision of the production flow. This component is responsible for: (a) capturing the information, that illustrates transformation from raw material into articles/pieces and later to final products in order to assign the carbon footprint; (b) examining the process steps undertaken, which machines are required and the exact duration of the process step; (c) supporting the calculation of the required Key Performance Indicators (KPI's) for the different levels of analysis and also considers the indirect energy consumption related to the production. In order to ensure the energy and carbon management across all processes in manufacturing, a component that is responsible to track the production processes and initiate the process of energy consumption and carbon footprint estimation is required. In terms of information flows, this element handles the environmental information flow, transactional information flow, contextual information flow, environmental information flow and product environmental information flow, as it is a central component of the proposed architecture.
- The **Energy Consumption and Carbon Footprint Estimator** includes the business logic for aggregating and disaggregating energy consumption at various levels of analysis,

transforming them into carbon emissions and then estimating the carbon footprint. This element incorporates allocation methodologies such as Life Cycle Assessment. More specifically, it (a) computes the carbon emissions of the activities (processes) of a manufacturing (emissions from machines, lighting, heating), and (b) calculates the embodied carbon emissions of the products by allocating the pre-computed emissions from activities to products. The carbon emissions are available: 1) per element of the manufacturing, and 2) per article. The requirements impose the need for calculating impacts at different levels. However, the calculation and allocation of environmental impacts is a complex process that it is based on various methodologies. Therefore, it is important that this logic is incorporated into an independent component, giving also the user the possibility to review and set the respective parameters used in the allocation logic. This element mainly handles the environmental information flow, but receives as input both contextual and transactional information.

- The **Report Generator** creates standard formatted reports that cover all the aspects of energy and carbon management in the supply chain (e.g. energy measurement, carbon footprint at different levels of analysis etc.). A dedicated reporting component is important in order for a user to perceive the system as one homogeneous entity. Presenting the calculation outcomes in a meaningful and user-friendly way is important for a user to understand a systems' value. Figure 5.3 depicts a view of the system reporting results.

Achieving energy and carbon management in the manufacturing demands the integration with external resources. Therefore, interfaces with the following existing systems should be developed existing systems (e.g. ERP, MES, BMS, LCI) in terms of accomplishing collaboration and interoperability (as presented in Figure 5.2).

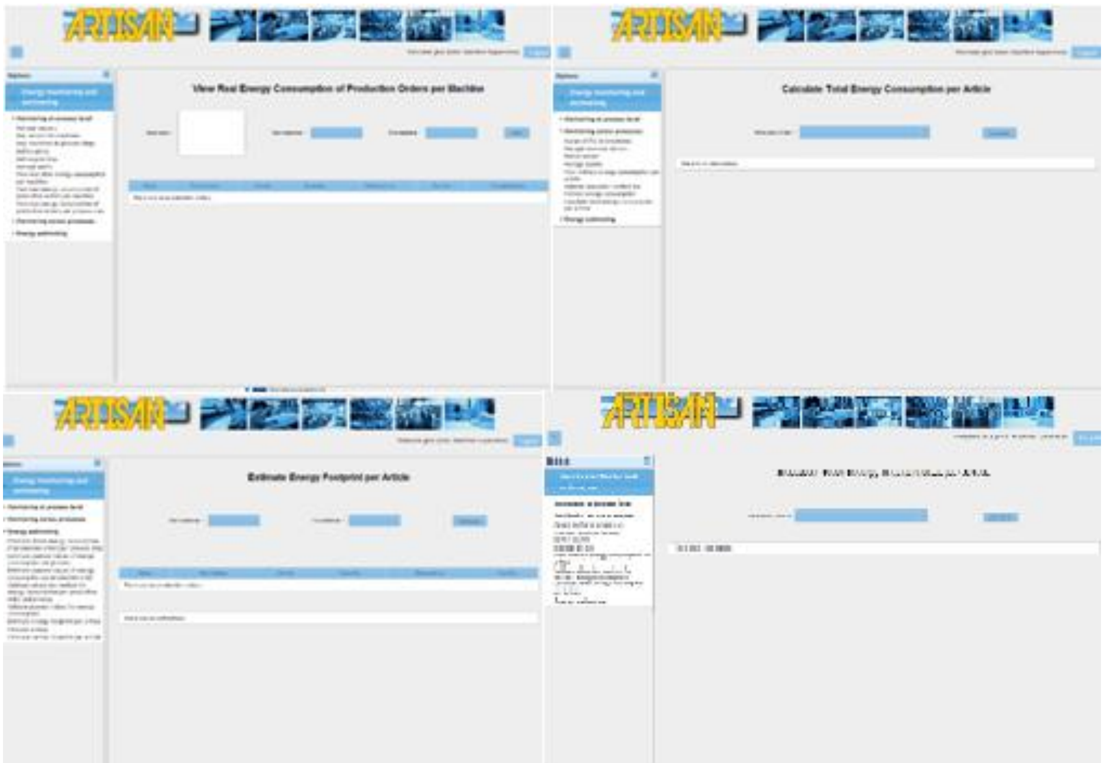

Figure 5.3: Energy and Carbon Management System Instantiation in Manufacturing

5.3 Demonstration and Evaluation

To probe and test the designed artifact in use and familiarize with any implementation issues, a system instantiation was developed and pilot tested. This system instantiation can be regarded as a basis of inquiry and interactive cognition. This means that it should had the properties required for its purposes and scope, and as few other properties as possible. To envision the three identified purposes and scope of energy and carbon management we installed three pilot configurations at each one of the two cases, one at a time. Since we defined the scope of demonstration, we investigated at first place the existence of the following systems: a) ERP that handles the requests of customers, articles, quantities to be produced, stocks of raw materials and technical data sheets of fabrics, b) MES that is more directly tied to the machines. It stores the settings of machines per product type and monitors performance, c) Energy Capturing Infrastructure that is responsible for collecting energy consumption data, d) COST that determines the cost of production, and is often missing or not integrated with the information of ERP.

To build this pilot testing environment, we installed the prototype system, the required interfaces with existing systems and any energy capturing infrastructures (e.g. sensors) in real-world settings within two companies, a leading textile manufacturer and an international clothing company (see 3.4.1 for more details). Moreover, a process for collecting, processing and validating the actual data that were necessary was deployed following the data specifications discussed in Section 5.2. The implementation process followed presented below:

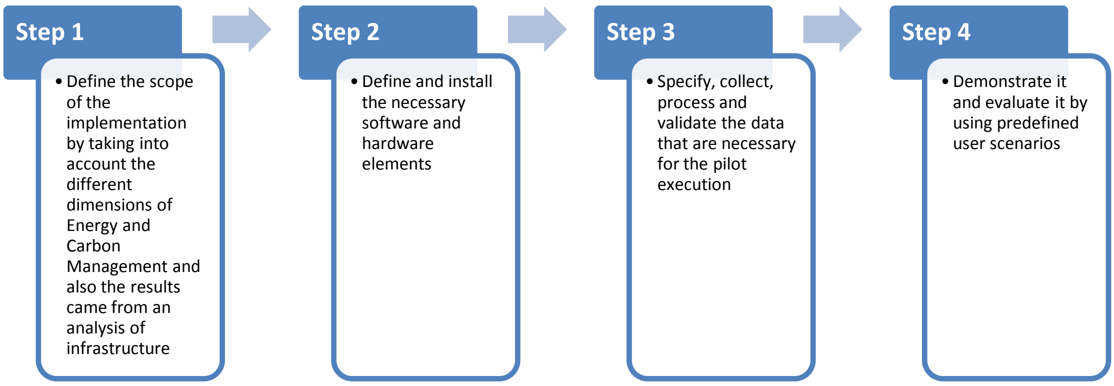

Figure 5.4: Implementation Process

The contextual information was sent only once during the initialization phase and then it was re-sent when updates were required. After discussions with the industrial users, it was decided to extract daily transactional data from their ERP and WMS systems respectively and upload them via FTP on the web platform for a period of six months. Moreover, any necessary software and hardware elements (e.g. energy sensors, interfaces) were installed. Below we discuss more details on the implementation process per Case. At each case, we pilot tested all three of the energy and carbon management levels.

In Case A, we focus on weaving, dyeing and finishing (wet finishing, raising and dry finishing) and a short analysis was conducted in order to select some of the most relevant energy consuming machines and systems in this case. We focused on the study of the most energy-consuming ones on one hand, and on the other hand on the ones where we have the unproductive time of production: the stenter machine, the fulling machines and the weaving department. More specifically, weaving is the production phases by which the warp (the parallel yarns rolled on a tube) becomes a fabric by the insertion of the weft (yarns orthogonal to the warp) by the loom. Case A weaving department has 38 looms which are represented by firm's MES. Due to the minimum lot dimension and fashion tendencies, fabric dying is less common for high market (the one where EU industries compete) while is most common for the mass one. Case A dyeing department 19 machines. Finishing is the part of the process which characterizes the surface touch of the fabric which, after the color, is the most critical quality of the fabric. While color is obtained by a standard process finishing is the combination of raw material melting with finishing. This part of the production includes a combination of several machines. The most important machines in Case A finishing are: 2 Fulling machines, 3 for vegetal raising, 3 for metal rising, 1 Stenter machine, 1 decatizing machines. Except from the above machines, we should take into account the machines (like steam boiler, compressed air, air filtering lighting, etc.) that generate the "indirect consumption" and can be measured along a period and reported over each department.

In Case A, an energy monitoring system is not installed. Energy data are collected only for accounting purposes and the division of costs between departments is estimated based on bills. Unfortunately, energy consumption is not considered as interesting information in itself. It is only considered as a monetary factor affecting the production costs of articles. Based on the current data availability, articles could not be grouped with certainty. To definitively group articles, a profile for each process step, is needed, making it possible to see differences between groups of items and/or give them an average time profile. The consumed energy can be divided into two categories: electrical power and gas. Other energy sources, steam, compressed air, air conditioning, warm water, are considered secondary sources and can be converted from the two primary sources. Since no energy monitoring system is currently in place, no energy data can be stored. Therefore, energy sensors were installed in order to monitor the energy consumption of the machines identified above. To evaluate the consumption of indirect energy, the energy consumption is measured for each department over a certain time and multiplied for the working time of a unit. It is then possible to summarize the direct and indirect energy for a unit into a single meaningful value. Moreover, some limited data from energy audits are available. An ERP and an EMS is installed and the respective interfaces should be developed. The cost package of the ERP system is used internally to estimate a cost for each article. This estimation takes into consideration the time spent in production (for each product unit) per department (cost center).

In Case B, the production consists of 2 major process steps: The knitting and the finishing, which includes digital printing. The knitting machines do consume a lot of electricity. The standby-consumption of those machines is insignificant, as the machines don't have to be heated. There are already very sophisticated processes in place (including a detailed status-tracking of the machine). So the knitting department was not the focus of the pilots, as the challenges here had already been managed by Case B. The finishing process does consume by far the most energy at Case B. This is due to a lot of steaming, washing and drying-processes. There are more than 10 different types of machines used. For some machine types, there is only one large machine available, for other machines types there are 7 individual machines. In general, the whole production logistic and logic is complex due to various facts e.g. different parts of an article follow different production order schedules, seasonality. The parts are routed independently in the finishing regarding most steps, but have to be processed together for some process steps. Due to the production logistic complexity of finishing, the machine utilization is quite low on average. Many machines have a standby-consumption similar to the production-consumption as the machines have to maintain their high temperature (e.g. 170°C). There is a major energy saving potential here.

if the standby-time of the machines can be reduced. In addition, those machines cause high indirect energy consumption. This is needed especially for the air-conditioning of the production buildings. All the extra heat dissipated by machines in standby-consumption has to be dealt with. The temperature and temperature related machine status, as "cooling-down", "heating-up" regarding turn-off and standby as well as different production temperatures have been identified as being a crucial part of the energy consumption behavior. Case B have recently installed an ERP/PPS (went live on August 2012) within production. So the situation and data-structures are changing a lot at the moment. However, they provided more of the requested data. In Case B, There was already a comprehensive electricity monitoring system in place at Marc Cain. Therefore, the energy consumption data already recorded were used.

During the pilot testing, the system was also evaluated in order to explain whether the non-functional requirements are met. The non-functional requirements have been collected from the input and the discussion with the business partners and were based on the Standard ISO/IEC model, which defines quality standards by identifying a set of features and attributes that a generic software needs to have. Moreover, a further evaluation of the artifacts was conducted by selected employees working in our study Cases in order to gain feedback about the efficiency of the system. They interacted with the system by executed a set of pre-defined scenarios and then completed a questionnaire for evaluation purposes. The results are presented in Appendix F.

5.4 Findings for the Design and Implementation

In the previous section, we presented in detail the instantiation of an ECMS in manufacturing, the artifact architecture and its respective components and the actual context under which it was implemented. In this section, we provide empirical evidence on the main issues we came across during the demonstration, pilot testing and evaluation of the ECMS in the manufacturing settings. These issues are related with the following aspects presented above a) Data quality and availability, b) Data capture and integration and c) Environmental Performance Metrics selection that are further elaborated below. Therefore, the existence and the integration of the aforementioned information flows has been the focus of this analysis, as this is a core consideration of such systems. Moreover, technical or process-related issues are further discussed. Insights on how these issues could be tackled are also provided. Evidently, these challenges reveal specific design and implementation principles to be implemented in order to ensure the efficacy of such systems in a real-world context. The design principles define what a system should provide in order to cover the requirements. The implementation principles concerned with the process of setting up and maintaining the proposed class of systems. The following key findings emerged from the demonstration, pilot testing and guided our effort to refine the design of an ECMS.

Therefore, these findings could become a guide towards the design and the implementation of ECMS in the Manufacturing. Note that we don't claim exhaustiveness.

More specifically, the various findings can be summarized in the following list:

- the environmental data availability
- the data quality and data inconsistencies
- the data granularity levels
- the complexity of integrating various types of data (e.g. energy consumption data with manufacturing data)

- technical integration issues and absence of automation mechanisms
- the dependencies and coordination problems in the workflow tracking due to the time-dependency of manufacturing data and the monitoring of semi-finished products
- the definition and selection of environmental and traditional performance measures

Below, we discuss each one of these findings and we conclude with a set of design and implementation principles guidelines that could be taken into account in order to design and implement an ECMS in the manufacturing.

Environmental data availability

One of the main problems of implementing ECMS is that the existing information systems don't typically store non-traditional manufacturing information, such as energy consumption, steam or any resources consumption. This information is needed in order to calculate environmental impacts and promote energy efficiency in manufacturing. In most of the cases, companies keep aggregated information for energy consumption for accounting and cost monitoring purposes. If they keep it, they store it on a monthly period based on the electricity bills, or, in some other cases, they manually record the energy consumption via physical energy audits. They even store it expressed in cost for a specific period of time, mainly for reporting purposes, and not per machine as required for energy and carbon management. However, there are also some cases where they have already installed energy power meters or building management systems. In these cases, integration issues are raised up as many types of energy meters cannot interoperate with other information systems. Within the context of manufacturing, the energy consumed is divided into different categories e.g. direct and indirect energy or actual, normal or planned as discussed above that should be taken into account (Section 3.4.2).

As the availability of the environmental information flow is a prerequisite for the implementation of an ECMS, the diversity and the limited environmental availability is an aspect that has affected the design of the ECMS and the respective data requirements. It affects the database schema. The ECMS managed both actual measurements of energy sensors and energy consumption based on secondary data (energy vectors) and makes the respective calculations. A dedicated component for the management of actual energy consumption data captured by energy sensors was developed called as Energy Sensor Monitoring and another one for handling secondary data called as Non-Sensor Energy Monitoring. As this component should be able to integrate with various sensors general standards regarding energy sensors were adopted.

Therefore, the following design principles suggest ways to increase the availability of environmental data and use all the available environmental data.

Design Principles:

In the design phase of an ECMS in Manufacturing, the following design principles could be taken into account:

a. The system should manage (collect, process and store) the various types of energy consumption e.g. both actual measurements of energy sensors and energy consumption based on secondary data in order to enable a company to implement energy and carbon management based on its current data availability levels.

b. The system should include configuration parameters referring to data availability in the components of an ECMS that are responsible for the data uploading and storing, for conducting the energy and carbon estimations and allocations and for managing and integrating all information flows in order to adopt energy and carbon management on a firm's data availability levels.

c. The system should implement mechanisms for producing environmental data based on secondary transactional data e.g. a mechanism for calculating energy consumption based on production data and energy vectors could be used as an alternative source of information.

d. The system should implement general standards regarding energy sensors in order to facilitate the integration with existing energy sensors infrastructure if needed.

e. The system should implement an interface that will inform users about the environmental data used in the calculations ensuring data transparency.

Implementation Principles:

a. In the implementation phase of developing an ECMS, the following steps concerned with the process of setting up the system would ensure the requisite environmental information flows. Define the type of energy consumption e.g. direct energy consumption and indirect energy, actual, normal or planned that should be collected and monitored and examine the environmental data availability.

b. Identify the technical infrastructures that will provide them (e.g. installed energy meters) and examine if any infrastructure investment (e.g. power meters) is needed.

c. Define the process of retrieving data (e.g. what interfaces and how they should be developed, how often the data should be sent)

d. Define the configuration of the ECMS related to data availability

Data quality and data inconsistencies

Many previous studies have investigated the poor data quality problem (e.g. on product information and process monitoring), and the negative impact that it has on both manufacturing information systems and decision support processes. However, many efforts have been conducted in order these problems to be addressed. In the case of the energy and carbon management, the need of detailed time-dependent information regarding production processes and the steps that are followed make questionable the provided data quality. For example, the Article_Step_Sequence information that maps articles on process steps and production phases should keep the start_time and end_time of a process step in order to allocate the energy consumption of a machine to the respective process steps and articles. However, in many cases the start_time is recorded and the end_time is missing. Moreover, energy consumption is differentiated at different phases even in a machine but information about the different phases of a machine is not a traditionally kept in the manufacturing systems. Besides, production seasonality creates new production patterns that affects the production processes and increases the complexity of monitoring the processes workflow as the updated information regarding new production processes is not available. Moreover, there are a couple of inconsistencies and difficulties in transforming data in compatible and comparable terms. For example, the energy consumption of some processes in some cases is not based on actual measurements but on secondary data come from energy audits which makes the comparability of outcomes negotiable. Moreover, various details about production processes are referred and computed for product unit. However, the unit for fabric is a meter, while for the garments the unit is an item.

Therefore, poor data quality and data inconsistencies were raised as one of the main issues of implementing these systems. During the pilot testing, we tried to restrain these problem by initially define an extended list of the data required and starting a process of mapping the existing with the required data. In cases of missing data, we define which of the system functionalities are eliminated and discuss if some of the missing data could be retrieved or produced in another way. For example, the article step sequence could not be retrieved automatically towards an interface from the existing systems. However, this information didn't change often and could be produced based on existing information at an initialization phase and then updated when is needed. Moreover, the Article Tracking information was essential for any allocations of the energy consumption but it was incomplete as the exact time of the production of each article was missing. For the missing Article Tracking Information, we developed time - profiles of the various articles for the different process steps and processes. Moreover, the received data should be validated and cleaned-up in order to be integrative and they should be compliant to the data specification standard. Moreover, a user should be informed about the available data quality on order to interpret the data in the right way.

Therefore, the following design principles suggest ways to tackle the poor and improve data quality and eliminate data inconsistencies.

Design Principles:

In the design phase of an ECMS in Manufacturing, the following design principles could be taken into account

a. The system should collect data that have been produced in a non-automatic way e.g. towards a user interface for uploading data that are kept in excel-like format

b. The system should deploy mechanisms that will transform the data in compatible forms e.g. comparative measurement units.

c. The system should deploy mechanisms and business logic that produce the missing data based on the existing ones e.g. the article tracking information

d. The system should provide a data-cleansing mechanism that will validate and clean-up the data received in order to be integrative.

e. The system should provide a mechanism that will ensure that the received data are compliant to the data specification standard.

f. The system should inform a user regarding data quality e.g. towards a user interface in order to interpret the results in an accurate way.

g. The system should provide an interface and mechanisms for designing the production processes and setting-up production processes parameters that are related with the poor data quality e.g. secondary data regarding energy consumption based on energy audits or time profiles of the processes

Implementation Principles:

In the implementation phase of developing an ECMS, the following steps concerned with the process of setting up the system could be taken into account for tackling the poor data quality and inconsistencies:

a. Define the full data dataset required for the system to support the selected Energy and Carbon Managements scope, The data requirements should also specify details regarding data granularity level by taking into account the following dimensions: time, product, physical unit (e.g. machine, process step, process, production order)

b. Examine whether the required data are available in the granularity level required and define the deficiencies in order to see if data deficiencies impact the provided system functionalities

c. Examine if the missing or incomplete data could be produced towards a non-automatic way and used as initialization data that will model the production processes at the system set-up phase.

d. Produce a full dataset based on the available data quality and inconsistencies and validate it towards a test case scenario.

Data granularity levels

The specification of the required data granularity level is one of the other major issues that were raised in this context. Even when the data of the transactional and environmental information flows were available, they were usually available at different granularity levels. Energy and Carbon Management in manufacturing is highly time-dependent which imposes the need of detailed data in terms of time. Environmental data can be either kept on a highly aggregated level, e.g. monthly, or can be too detailed, as energy sensors can record energy consumption even on few seconds basis. Moreover, an energy sensor sometimes should be linked with a group of machines. In that case, the allocation of energy consumption to the exact process steps and articles is difficult and not accurate. Besides, energy consumption is also differentiated at the three different phases of a machine. However, information about the three different phases for each machine isn't usually kept. These different granularity levels are also one of the main obstacles of integrating the various information flows.

Defining the right data granularity level based on the available information flows ensures that the various information flows can be integrated. In our cases, we concluded that the exact time of transactional data are required in order to ensure both the applicability of an ECMS and also the meaningfulness of the results. By taking into account the aforementioned constraints and also the initial requirements, we concluded that the granularity level was one of the basic parameters of the ECMS and it was incorporated in the Data Layer components that is responsible for the data uploading and data storage processes, the Energy Consumption and Carbon Footprint Estimator component that estimates the energy and carbon emissions and the Transactions Flow Network Monitoring that handles all the information flows. Moreover, we concluded that collecting and monitoring information on a detailed time level has increased complexity that could not ensure the applicability of an ECMS. So, the definition of granularity level based on the trade-off between complexity and the level of detail of the information is a critical decision.

The following design principles suggest ways to ensure the same granularity levels in the received data.

Design Principles:

In the design phase of an ECMS in Manufacturing, the following design principles could be taken into account

a. The system should incorporate the data granularity as a basic configuration parameter in the components of an ECMS that are responsible for the data uploading and storing, for conducting the energy and carbon estimations and allocations and for managing and integrating all information flows.

b. The system should provide mechanisms that will transform data in the same granularity level e.g. mechanisms for aggregating energy consumption data on the granularity level in order to be the same with inventories granularity levels

Implementation Principles:

In the implementation phase of developing an ECMS, the following steps concerned with the process of setting up the system would ensure the same granularity levels.

a. Examine the granularity levels of the required data that are defined in the specification of data requirements for an ECMS

b. Define the granularity levels by taking into account the available granularity levels but also other aspects such as the objective of energy and carbon management or the trade-off between the value of detail and cost of collecting, processing and keeping detailed information

Complexity of integrating various types of data (e.g. energy consumption data with and production processes data)

One of the major issues that were confronted was the complexity of integrating the various information flows. The aforementioned problems were merely responsible for this problem as the integration of the various flows required a common granularity level, a complete and accurate dataset and the availability of all data. During the integration process, the comparability of the results should also be taken into account. For example, we could not compare the environmental impact of two processes if we have used different allocation process e.g. accurate time information on one case and estimated time profiles on another case or different allocation parameters e.g. weight, volume, article. Moreover, we should follow specific rules based on the available data. As long as the machine / MES does provide the start time and end time of each production order and a time profile for the energy demand of this machine is available, the energy demand of each order can be derived. If setting-up and cleaning processes due occur, the time spans of those should be available, too. Therefore, an adaptable logic of integrating the various flows and allocating the environmental impacts at different levels of analysis has been deployed in our case and was the main responsibility of the Energy and Carbon Estimator Component. The logic initially examines the data availability and presents a set of information availability measures. Then, the user uses this information and defines some parameters and the respective computation logic of the environmental impacts is applied.

Therefore, the following design principles suggest ways to address the integration of the various data types.

Design Principles:

In the design phase of an ECMS in Manufacturing, the following design principles could be taken into account

a. The system should provide an adaptable logic of calculating and allocating environmental impacts at various levels of analysis by taking into account data granularity level, data accuracy and the availability of all data.

b. The system should inform the user about the allocation logic or the standard implemented in order to enable him to compare and interpret the results.

Implementation Principles:

In the implementation phase of developing an ECMS, the following steps concerned with the process of setting up the system would ensure the integration of the various information flows.

a. Defining the parameters that will configure the calculation and allocation logic of the environmental impacts. The parameters will take into account the following aspects, data granularity level, data accuracy and the data availability.

Technical integration issues and absence of automation mechanisms

Except from the data-related issues that have been mainly discussed above, many technical issues should also be addressed. Starting from the environmental data, the integration with existing BMS and energy sensors and the retrieval of energy consumption data was a demanding process. It required not only the development of interfaces but also the development of mechanisms that ensure that we continually received the energy data. Moreover, environmental data was also recorded by using spreadsheet-like solutions and the integration and retrieval of environmental data should be automated. Automation was a difficult task in this case, as these data were not produced daily and a more sophisticated way of calculation should be developed; e.g. develop a mechanism that calculates energy consumption based on secondary data come from energy audits.

Moreover, integration and automation with existing systems e.g. ERP is also critical and is not straightforward. In our cases, one of our users had newly developed and installed ERP that was keeping information regarding production processes, articles, orders. However, none of our users had an experience on cases of mass data retrieval and information exchange mechanisms. Therefore, the deployment of interfaces and information sharing mechanisms turned to be a demanding and repetitive process in order to end up with a complete dataset and ensure an acceptable level of data quality.

Therefore, the following design principles suggest ways to facilitate the technical integration and automation.

Design Principles:

In the design phase of an ECMS in Manufacturing, the following design principles could be taken into account:

a. The system should use technologies that support componentization and can improve the reusability, interoperability and integration of the systems such as, object-oriented design, web services, eXtensible Markup Language (XML), and service-oriented architecture.

b. The system should provide various interfaces options in order to automate data retrieval from various systems e.g. ftp, web-services. .

Implementation Principles:

In the implementation phase of developing an ECMS, the following steps concerned with the process of setting up the system would facilitate the technical integration and automation.

a. Define the existing systems with which the ECMS should interact in order to retrieve data in an automated way

b. Investigate the existing level of automation and define the way and the technologies that the systems will interact e.g. interfaces, web services

c. Investigate the existing level of information exchange and try to leverage existing information exchange relationships.

d. Define the effort needed for developing automation mechanisms and decide if automation is suggested e.g. if data are required only at system set up phase an automation process may be skipped

e. Conduct a repetitive process of data retrieval from existing systems for tackling integration and automation issues but also ensuring that a complete dataset with an acceptable level of data quality will be available.

Dependencies and coordination problems in the workflow tracking due to time-dependency of manufacturing data and the need of monitoring semi-finished products

The implementation of ECMS in manufacturing, where the transformation of raw materials to finished products takes place, increases the complexity of implementing energy and carbon management due to various flow dependencies and coordination problems. For example, the type of product usually changes during the production. Often one article is cut into many different articles (weaving, same chain for several fabrics, or knitting of a ribbon which is cut in pieces) or many articles are combined to one new article (sometimes just to be processed in the next production step and to be separated again later). Therefore, a mapping between higher level items with their components is required. The bill of material covers the aforementioned need as it connects higher level items with their components. Moreover, the production seasonality creates new production patterns that demand the coordination of various systems and the synchronization of the various data. Dependencies and coordination problems are also raised due to the fact that the workflows for different articles especially regarding the energy intense finishing process steps do vary a lot. Nevertheless, it may be possible to define product-groups with similar workflows.

In general, dependencies in environmental and product information acquisition are mainly resulted by the need of tracking the workflow of various units, process steps, processes, articles, production orders in order to perform the energy consumption allocation which is intense time-dependent at the various levels of analysis. For example, we should know the exact start time that a process starts and ends in order to allocate the right amount of energy consumption.

Therefore, the following design principles suggest ways to facilitate the inputs alignment from various supply chain partners.

Design Principles:

In the design phase of an ECMS in Manufacturing, the following design principles could be taken into account:

a. The system should provide a feature that maps and monitors the transformation of raw materials to semi-finished or finished products by using the BOM existing information

b. The system should provide mechanisms that support the coordination of all workflows by taking into account the intense time dependencies

c. The system should provide the ability of modeling the varieties of the production processes e.g. production seasonality, great variation of production steps and processes at the different articles.

Implementation Principles:

In the implementation phase of developing an ECMS, the following steps concerned with the process of setting up the system would facilitate the workflow tracking.

a. Define the workflows that should be tracked (e.g. articles, orders) and then examine if the available workflows should be synchronized.

b. Define the processes that transform the type of the article for example from raw materials to semi-finished products order to investigate the potential coordination problems and use them as test case scenario later on.=

c. Define the processes, process steps, article with the greatest alignment in order to investigate the potential coordination problems and use them as test case scenario later on.

The definition and selection of environmental and traditional performance measures

Despite the fact that energy and carbon management has a growing interest, there was no standardized Key Performance Indicators that could be calculated on a detailed basis by taking into account the exact operational production data and the respective energy consumption ones. Therefore, one of the main issues that were raised was to define the indicators that should be calculated. The definition of indicators is closely related with the objectives of energy and carbon management and should be aligned with the overall goals. For example, in textile manufacturing industry the focus is on cost reduction that comes from energy consumption. Therefore, a more extended list of energy related indicators that covers all types of energy e.g. direct, indirect s is required. These performance indicators should cover both the traditional operational aspects and the environmental ones. Moreover, the need of using integrated indicators that incorporate both environmental and operational aspects came up. For example, CO_2 efficiency and CO_2 effectiveness have been measures that were defined to combine the environmental impact of a production process with the volume of products that have been produced. Moreover, the product/article level of analysis came as an important one. Therefore, performance indicators that refer to produced products/ articles should be defined and selected. Many approaches have been proposed in the literature. However these indicators are usually not so detailed. Their applicability on a daily basis by using actual data has to be examined and the respective assessment methodology should be defined. In our case, we adopted a series of indicators, presented in previous section, in order to cover various environmental and operational aspects and integrate them in integrated measures. As this list is not an extensive one, the system should give the ability to a user to expand the specific list of KPIs and even to create their own set KPIs.

Therefore, the following design principles suggest ways to define and select energy and carbon indicators.

Design Principles:

In the design phase of an ECMS in Warehousing and Distribution, the following design principles could be taken into account

a. The system should implement a list of various assessment methodologies and energy and carbon management standards.

b. The system should provide a list of a list of various energy and carbon indicators.

c. The system should provide a user the ability to create new energy and carbon indicators if the data are available

Implementation Principles:

In the implementation phase of developing an ECMS, the following steps concerned with the process of setting up the system would define the energy and carbon indicators.

a. Select the energy and carbon indicators that should be monitored and create new ones if needed in order to support decision making processes and the implementation of sustainable supply chain practices

b. Select the assessment methodology and energy and carbon management standards that should be followed in order the outcomes to be comparable.

5.5 Capturing Knowledge for Impact gained from Artifact Demonstration

Energy and Carbon Management is one of the prominent issues for promoting energy and carbon efficiency in manufacturing (Bunse et al., 2011) and in that way the development of environmentally sustainable supply chains (Seuring & Müller, 2008). Measuring energy efficiency is the basis for controlling energy consumption in the production processes, for deciding about improvement measures and for tracking changes and improvements in energy efficiency (Bunse et al., 2011; Karnouskos et al., 2009). Moreover, the integration of energy efficiency into production management is one important lever to enhance production systems towards energy efficiency as it may be the basis for successfully implementing energy efficiency improvement measures. Within this context, ECMS are recognized as a key resource to support organizations in the development of energy and carbon efficient manufacturing (Bunse et al., 2011) by measuring energy and carbon emissions and enabling energy and carbon management. More specifically, ECMS collect, integrate and calculate energy and carbon emissions in various levels of analysis promising to increase awareness and visibility of energy consumption and carbon emissions in the manufacturing (Vikhorev et. al, 2013). Moreover, ECMS are expected to impact the enablement of environmental sustainable supply chains by supporting environmental-aware decision-making in manufacturing (Bunse et al., 2011; Vikhorev et. al, 2013) and sustainable manufacturing practices implementation (Seidel et al., 2013). The ultimate goal of this section is to provide some first empirical evidence on how ECMS impact the implementation of environmentally sustainable supply chains, as well as to highlight how the data collected by an ECMS and the functionalities provided by them could be leveraged in order to support energy and carbon management and sustainable supply chain practices in manufacturing. In that way, we are going to provide evidence on the testable propositions discussed in Section 4.3.

In a nutshell, the ECMS collect energy and fuel consumption (e.g. from energy sensors, energy management systems, building management systems and secondary sources as energy vector) and report them even in real-time, collect other traditional supply chain related data (production and distribution data) from existing systems (e.g. ERP, MES, WMS) and integrate them with the energy and carbon ones in order to calculate environmental and traditional supply chain performance indicators. Moreover, they support the integration of energy management with production management towards enhancing energy and carbon efficient manufacturing (Bunse et al., 2011).

Below, we present a series of scenarios of energy and carbon management that were defined based on the purpose and scope of energy and carbon management (Section 4.2) and the interaction with the users during the system demonstration and evaluation, some exemplary relevant questions and how the ECMS impact their implementation by collecting the data required and providing various KPIs. More specifically, we provide empirical evidence on how the ECMS contribute on answering these specific questions by taking into account the KPIs, data and system functionalities required to support them. We don't intend to deploy an exhaustive list of questions and scenarios but to provide some proof-of-concept examples as they came during the evaluation phase with the users.

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Table 5.4: Energy and Carbon Management Scenarios/ Examples

Energy and Carbon Management Scenarios/ Examples	Exemplary Decisions/ Questions to be answered	KPIs Required	Data Required and Granularity Level	ECMS Role
Manage energy and carbon emissions of production machines and compare them	• Which is the energy and carbon efficiency of the production machines? • Which is the more inefficient machine in terms of energy consumption and carbon emissions? • How much the energy and carbon efficiency of a specific production machine differs among the various processes?	• The KPIs required and their respective level of analysis is defined at Table 5.2. including e.g. in Total Energy consumption, Energy efficiency (KWh/reference unit of the level of analysis), Machine Idle Time • The KPIs are calculated by taking into account the selected time frame	• The data required are defined at Table 5.3 (Managing energy consumption and carbon information at process level column). • The contextual data should be collected once at the initialisation phase. • The transactional and environmental should be almost in the same time frame in our case almost in real time collected.	• The ECMS collects the energy consumption data (e.g. from the new installed energy sensors and the existing building management systems) by using **Energy Data Layer** and **Energy Sensor Monitoring** and its respective interfaces. • The ECMS collects the rest data from the retailers' internal ERP/ WMS systems by using **Operational Data Layer**. • The ECMS through **Transactions Flow Network Monitoring** component integrate the data and calculates the KPIS required. For the calculations, it uses the **Energy Consumption and Carbon Footprint Estimator** component where the business logic for aggregating and disaggregating anticipated energy consumption, transforming them into carbon emissions and then estimating the carbon footprint is nested. • The ECMS towards the **Supply Chain Design and Modeller** supports the selection of the specific machines and the design of the production processes that includes them.

				• The calculated KPIs for the specific stores are presented towards the **Report Generator**. Figure 5.5 shows the outcome of this example.
Managing energy and carbon information of production processes and compare them	• Which are the energy consumption and carbon emissions at the production processes and the respective orders? • Which process is the most inefficient in terms of energy consumption and carbon emissions? • Which is the energy and carbon efficiency of a specific article across the production processes? • How much the energy and carbon efficiency of a specific article differs among the various processes?	• The KPIs required and their respective level of analysis is defined at Table 5.3. including e.g. in Total Energy consumption, Energy efficiency (KWh/m2), • The KPIs are calculated by taking into account the selected time frame	• The data required are defined at Table 5.3 (Managing energy consumption and carbon information across processes). • The contextual data should be collected once at the initialisation phase. • The transactional and environmental should be almost in the same time frame in our case almost in real time collected.	• The ECMS supports this example by following the process and using the components described above. • Figure 5.6 shows the outcome of this example
Managing energy and carbon information of a production order by using estimations	• Which are the energy consumption and carbon emissions at the production processes and the respective orders? • Which process is the most inefficient in terms of energy consumption and carbon emissions?	• The KPIs required and their respective level of analysis is defined at Table 6.7 and Table 6.3 including e.g. in Total Energy consumption, Energy efficiency (KWh/m2), Machine Idle	• The data required are defined at Table 5.3 (Managing energy consumption and carbon information at an aggregated level	• The ECMS supports this example by following the process and using the components described in the first example. As the energy consumption and carbon emission calculations are not based on actual data but on secondary data named as energy vectors, both **Energy Data Layer** and

	• Which is the energy and carbon efficiency of a specific article across the production processes? • How much the energy and carbon efficiency of a specific article differs among the various processes? • How much the energy and carbon efficiency based on real data differs for energy and carbon efficiency that is based on estimations?	Time • The KPIs are calculated by taking into account the selected time frame	column). • The contextual data should be collected once at the initialisation phase. • The transactional and environmental should be collected daily.	**Energy Sensor Monitoring** aren't needed. The energy consumption data are produced by using secondary data with the support of the **Non-Sensor Monitoring.** • Figure 5.7 and 5.8 shows the outcome of this example.

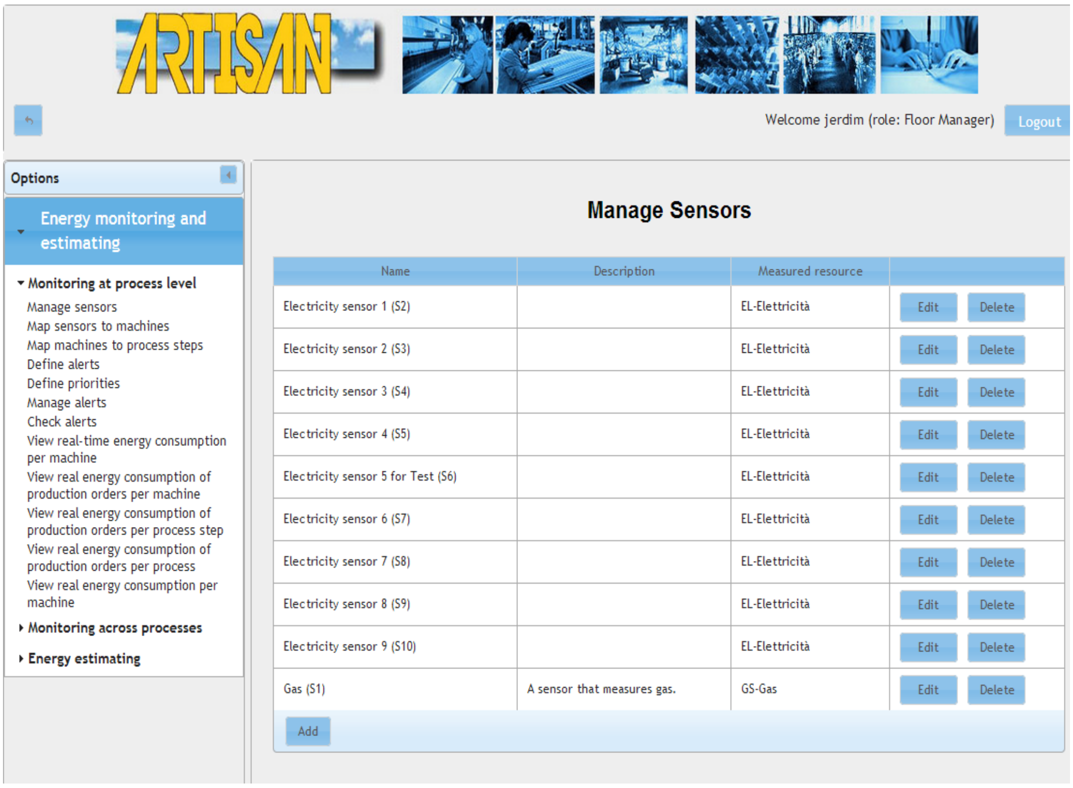


Figure 5.5: Manage energy and carbon emissions of production machines and compare them

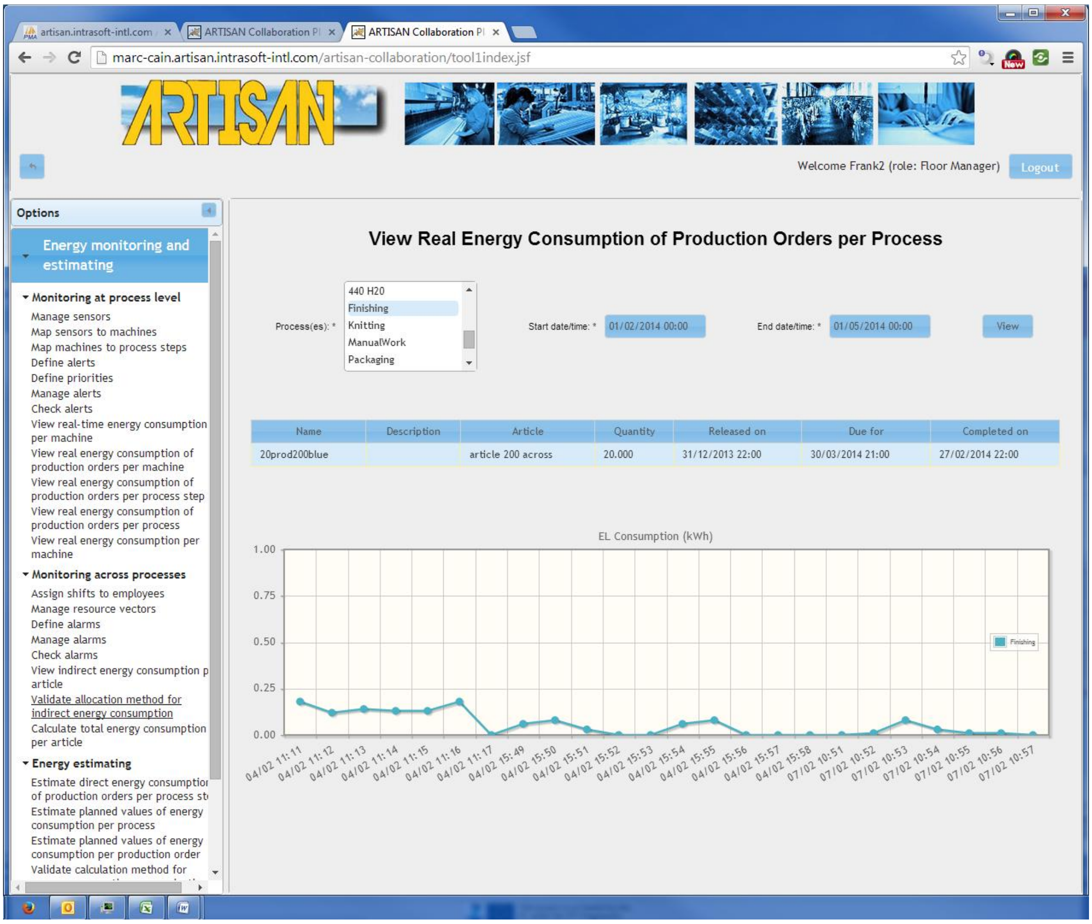
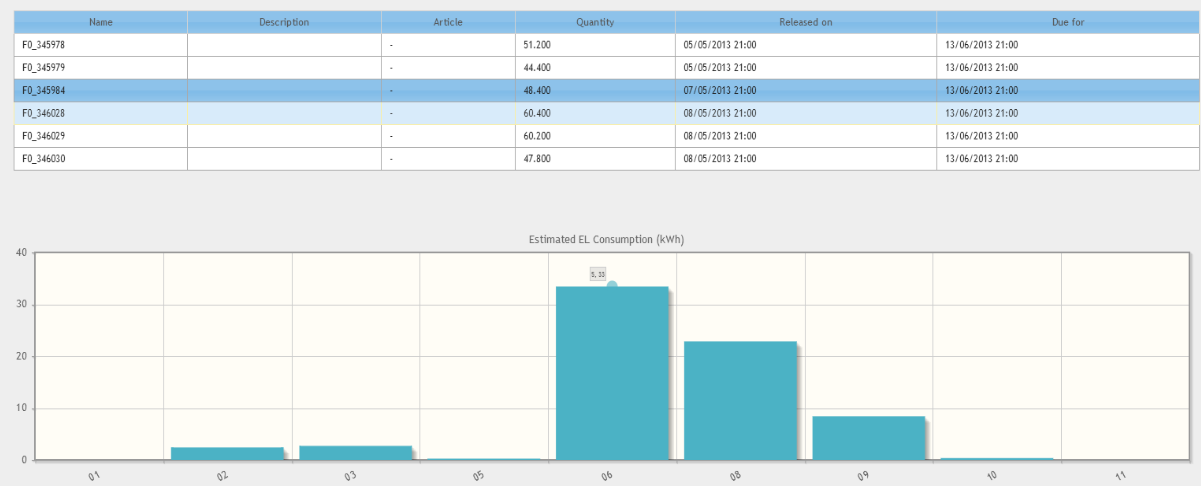


Figure 5.6: View Real Energy Consumption of Production Orders per Process



Name	Description	Article	Quantity	Released on	Due for
F0_345978		-	51.200	05/05/2013 21:00	13/06/2013 21:00
F0_345979		-	44.400	05/05/2013 21:00	13/06/2013 21:00
F0_345984		-	48.400	07/05/2013 21:00	13/06/2013 21:00
F0_346028		-	60.400	08/05/2013 21:00	13/06/2013 21:00
F0_346029		-	60.200	08/05/2013 21:00	13/06/2013 21:00
F0_346030		-	47.800	08/05/2013 21:00	13/06/2013 21:00

Figure 5.7: Managing energy and carbon information of a production order by using estimations

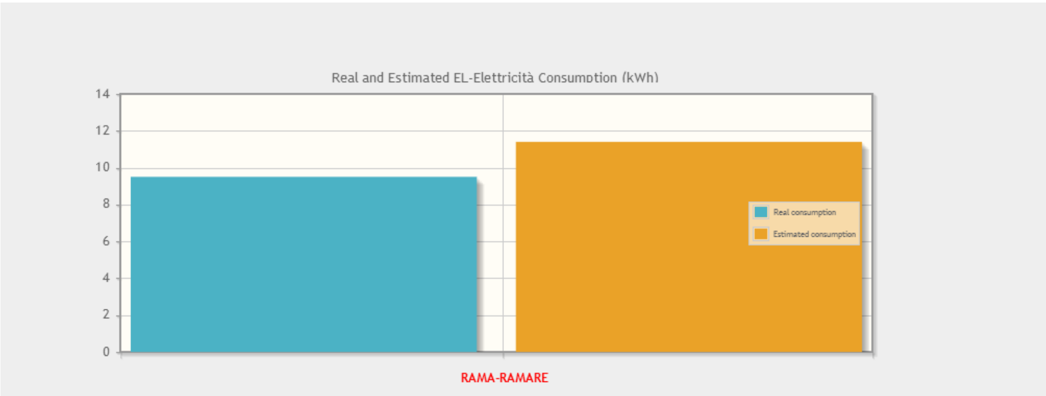


Figure 5.8: Comparison of the measured Energy consumption (real/actual) with the estimated values.

Aided by the energy and carbon management process presented above and by leveraging the data and the KPIs calculated and presented above, ECMS could support environmental - aware decision-making in the manufacturing. Some indicatively types of decisions that came from our cases and could be supported are the following:

- Reengineering the plant in terms of production infrastructure, for example reduce the use of the inefficient machines and or investigate the potential of replacing these machines if the energy cost is high
- Scheduling machines maintenance based on energy use pattern (e.g. predictive, proactive maintenance).
- Evaluate the production scheduling by taking into account energy consumption and optimize it
- Change jobs routing, when there is sufficient machine flexibility to do so in order to enhance energy-efficiency
- Defining energy consumption for a machine in different configurations (e.g. speed), and then choosing the more efficient machine configuration.
- Reducing idle time by switching a machine off, if energy consumption in Off/On transition is less than energy waste during idle time.
- Reducing energy consumption at peak time (e.g. load balancing)

Moreover, energy and carbon efficient manufacturing practices could be developed by leveraging the data and the KPIs calculated and presented in Table 6.5. In our cases for example, it supports the practice of energy -aware optimization production scheduling at the finishing mill. The primary scope of this practice is to reduce the direct and indirect energy consumptions via sophisticated energy-aware optimization methods. In particular, the aim is to deliver optimal scheduling scenarios and master production plans with the objective to improve all time related factors of the underlying production processes (i.e., to reduce the total running, deadhead and setup times of different sub-processes and machines) - assuming constrained resources - and simultaneously to address productivity, carbon footprint, and peak load of common resources. The description of the optimization logic is out of the scope of this section as our aim is to show how the ECMS collects and integrates data from the various resources (e.g. Retailers and Suppliers ERP, WMS) in order to feed with the appropriate data and KPI's the optimization logic and algorithms. More specifically, the ECMS collects, integrates and feeds the following data in an automatic way:

- Articles
- Article Tracking
- Production Orders (e.g., quantity, release dates, due date etc)
- Schedules
- Article Step Sequences (including operation types and changeover times)
- Process Steps and Production Phases
- Resources
- Machines (including Machine Availabilities)
- Resource Consumption
- Alarm Levels
- Direct and Indirect Energy Consumptions

6 INSIGHTS FROM DEMONSTRATION AND EVALUATION IN WAREHOUSING AND DISTRIBUTION

6.1 Introduction

The aim of this chapter is to present how the Energy and Carbon Management System artifact has been designed, developed and deployed in two cases studies in the warehousing and distribution. Having as starting point the outcome of Section 4, we elucidate them in the context of warehousing and distribution by capturing and presenting more precise system requirements, data requirements and KPIs. Then, we specify the components that incorporate these requirements, the architecture of the artifact, the design principles of each system component and provide an artifact instantiation. Then, we describe the exact real-case settings under which we implemented the two systems and the implementation process. The step of evaluation is conducted in two phases, so that the first phase could give feedback to the second round of design and development. The first round revealed a set of challenges imposed e.g. by the limited environmental data availability. Evidently, these challenges reveal specific design and implementation principles to be implemented in order to ensure the efficacy of such systems in a real-world context. We conclude by providing evidence regarding the impact of these systems on the enablement of environmental sustainable supply chains by supporting energy and carbon management, environmental-aware decision-making and sustainable supply chain practices implementation.

As discussed in Section 4.2, Energy and Carbon Management for manufacturing is recommended to be handled separately from warehousing and transportation, as this allows for analysis and details focused on manufacturing specifics. Therefore, we present below the evidence from warehousing and distribution cases.

6.2 Energy and Carbon Management System Design and Development in Warehousing and Distribution

Within the context of this study, energy and carbon management consists of three scopes. The first level refers to energy monitoring at the warehouse/store, the second level refers to distribution processes and the third one to supply chain. We describe each one of the levels below:

- **Managing energy and carbon information for warehousing.** This type of energy and carbon management requires the collection of energy data from various data sources (e.g., sensors) and the calculation of energy consumption at different 'granularity' levels, e.g. per facility, per store/warehouse, per section, such as refrigeration etc. It further needs the collection of operational data from existing systems in order to monitor traditional warehousing indicators such as inventory levels and associate environmental performance to utilization indexes. Such information allows for monitoring, controlling and improving environmental impacts of warehousing processes while also supporting environmental-based decisions.
- **Managing energy and carbon information for distribution activities.** This type of energy and carbon management requires the collection of fuel data from various data sources

(e.g., refills) and the calculation of energy consumption at different ‘granularity’ levels, e.g. per vehicle, per distribution link, per supplier, per route. There is also the need to monitor except from the environmental related indicators also traditional ones such as vehicle fill rate, distance travelled, weight distributed. Such information allows for monitoring, controlling and improving environmental impacts of distribution processes, while also supporting environmental-based decisions regarding distribution. It could also be used for supporting reporting objectives.

- **Managing energy and carbon information across the supply chain**. This type of energy and carbon management combines the two previous views (warehousing/distribution) and extends beyond a company's boundaries to cover the whole supply chain. Both energy and fuel consumption data are collected from different nodes in the supply chain and the scope monitoring is extended to supply chain partners. Such information allows for monitoring, controlling and improving environmental impacts in the supply chain and analyzing the existing ordering and distribution processes. This information is also used for supporting environmental-based decisions regarding collaborative solutions such as collaborative ordering and distribution processes by taking into account environmental aspects.

One of the key issues in the energy and carbon management is the specification and the definition of the performance indicators that should be monitored. The type of indicators in terms of system design is critical in order to define the data related requirements and their granularity (in terms of time and level of analysis) and also guide the deployment of the respective calculation logic. We have identified above three different levels of energy and carbon management in the scope of manufacturing and the respective level of analysis. However, we should expand each one of them by identifying a set of KPIs. The Key Performance Indicators that were developed take into account the following aspects: the type of indicator (environmental, operational, and integrated) and the level of analysis as (presented in Table 6.1) and the measuring unit. The KPIs identified are limited as the objective is not to define an exhaustive list of KPIs that would serve business goals but to identify a series of challenges that would affect the design and the implementation of Energy and Carbon Management System and to provide a proof-of -concept.

Below we present the various level of analysis and the key performance indicators based on the aforementioned aspects.

Table 6.1: Level of analysis in Warehousing and Distribution

Level of analysis
Store/warehouse section
Store/warehouse
Vehicle
Distribution link
Route
Supply chain networks
Product category / Product

Table 6.2: Key Performance Indicators in Warehousing

Indicator	Type	Level of Analysis	Formula	Measuring Unit
Total Energy consumption	E	Store/warehouse section, Store/warehouse, Product category, Product	-	KWh
Total CO_2e emissions	E	In all level of analysis	-	kg
Average number of products stored	O	Store/warehouse section, Store/warehouse, Product Category/Product	-	items, pallets, tone, kg
Total number of products sold	O	Store section, Store	-	items, pallets, tone, kg
Total number of outbound products	O	Warehouse section, Warehouse	-	items, pallets, tone, kg
Area	O	Store/warehouse section, Store/warehouse	-	m^2
Service level	O	Store/warehouse	AVG #orders covered in time) / Total #orders	-
Inventory rotation	O	Product Category/Product	Total turnover of a product/ product category sold / average product/ product category stock level	-
Energy efficiency	I	Store/warehouse section, Store/warehouse	Total energy consumption/ warehouse-store's area	KWh/m2
Space_CO2e efficiency	I	Store/warehouse section, Store/warehouse	Total CO2e per warehouse-store/ warehouse-store area	Kg CO2e/m2
Inventory_CO2e efficiency	I	Store/warehouse section, Store/warehouse, Product Category/Product	Total CO2 emissions / total number of products stored	kg CO2e / item stored, kg CO2e / pallet stored, kg CO2e / tone, kg CO2e / kg stored
Node_CO2e effectiveness	I	Store/warehouse section, Store/warehouse, Product Category/Product	Total CO2e emissions / total number of products sold	Kg CO2e / item sold, Kg CO2e / tone sold, Kg CO2e / kg sold)

Table 6.3: Key Performance Indicators in Distribution

Indicator	Type	Level of Analysis	Formula	Measuring Unit
Total fuel consumption	E	Vehicle, Distribution link, Route, Supply Chain Network		litre
Total CO2 emissions	E	Vehicle, Distribution link, Route, Supply Chain Network, Product category / Product		kg
Distance travelled	O	Vehicle, Distribution link, Route, Supply Chain Network		km
#Products Distributed	O	Vehicle, Distribution link, Route, Supply Chain Network		items, pallets, tone, kg
Vehicle fill rate	O	Vehicle, Distribution link, Route Supply Chain Network	avg (number of loaded pallets/ vehicle capacity in pallets)	-
Transport_CO2_efficiency	I	Distribution link, Route Supply Chain Network, Product category / Product	Total CO_2e emissions / (total km travelled * total number of products distributed)	kg CO_2e / itemskm, kg CO_2e / palletskm, kg CO_2e / tonnekm, kg CO_2e / kgkm
Transport_CO2_ effectiveness	I	Distribution link, Route Supply Chain Network, Product category / Product	Total CO_2 emissions / total number of products distributed	kg CO_2e /items, kg CO_2e / pallets, kg CO_2e / tonne, kg CO_2e / kg
CO2_effectiveness	I	Supply Chain Network, Product category / Product	Transport_CO2 effectiveness + Node_CO2 effectiveness	

All the aforementioned KPIs should be calculated on a daily basis. For a specified time period, the energy efficiency, space_CO2e efficiency, inventory_CO2e efficiency, node_CO2 effectiveness, Transport_CO2_efficiency and Transport_CO2_ effectiveness KPIs are estimated by taking the average of the daily calculated values of the respective KPIs.

In order to support the energy and carbon management level and the calculation of the various KPIs, we have identified the data entities and the respective data flows that are required. The data entities were classified in the following categories of information flows: Transactional information flow (TI), Contextual information flow (CI), Environmental information flow (EC), Product environmental information flow (PEIF). Figure 2 (Appendix D) depicts data entities along with their respective flows in a unified data model. Additionally, a description of these entities appears in Table 2 (Appendix D). The data model and the table present the minimum required list of data entities that are required in order to support the three levels that have been defined in warehousing and distribution. Despite the fact that the integration of all information flows is required in all cases (Table 6.4), there is no need for the extensive data set in order to support all of them.

Table 6.4: Data requirements per monitoring levels in supply chain

Data Entity	Managing energy and carbon information for warehousing	Managing energy and carbon information for distribution activities	Managing energy and carbon information across the supply chain
Partner		√	√
Vehicles		√	√
Vehicle Type		√	√
Functional Nodes	√	√	√
Functional Nodes Sections	√		√
Product Categories	√	√	√
Products	√	√	√
Product Details	√	√	√
Product Assortment	√		√
Smart Meter	√		√
POS (Sales)	√		√
Shipments		√	√
Deliveries		√	√
Delivery Batches		√	√
Route		√	√
Order	√	√	√
Inventory Levels	√		√
Fuel Consumption		√	√
Node Energy Consumption	√		√
Product Carbon Footprint			√

The distributed and heterogeneous environment in which Energy and Carbon Management Systems operate imposes the need of using technologies that support componentization and can improve the reusability and integration of the systems such as, object-oriented design, web services, eXtensible Markup Language (XML), and service-oriented architecture. Based on the above, the architecture of the artifact was designed. The logical view of the architecture is depicted in Figure 6.1 and shows a logical decomposition of the system's components that will interact in order to support the desired energy and carbon management levels. Last but not least, an ECMS needs to meet some non-functional requirements (see Appendix F). The non-functional requirements have been collected from the input and the discussion with the business partners and were based on the Standard ISO/IEC model, which defines quality standards by identifying a set of features and attributes that a generic software needs to have.

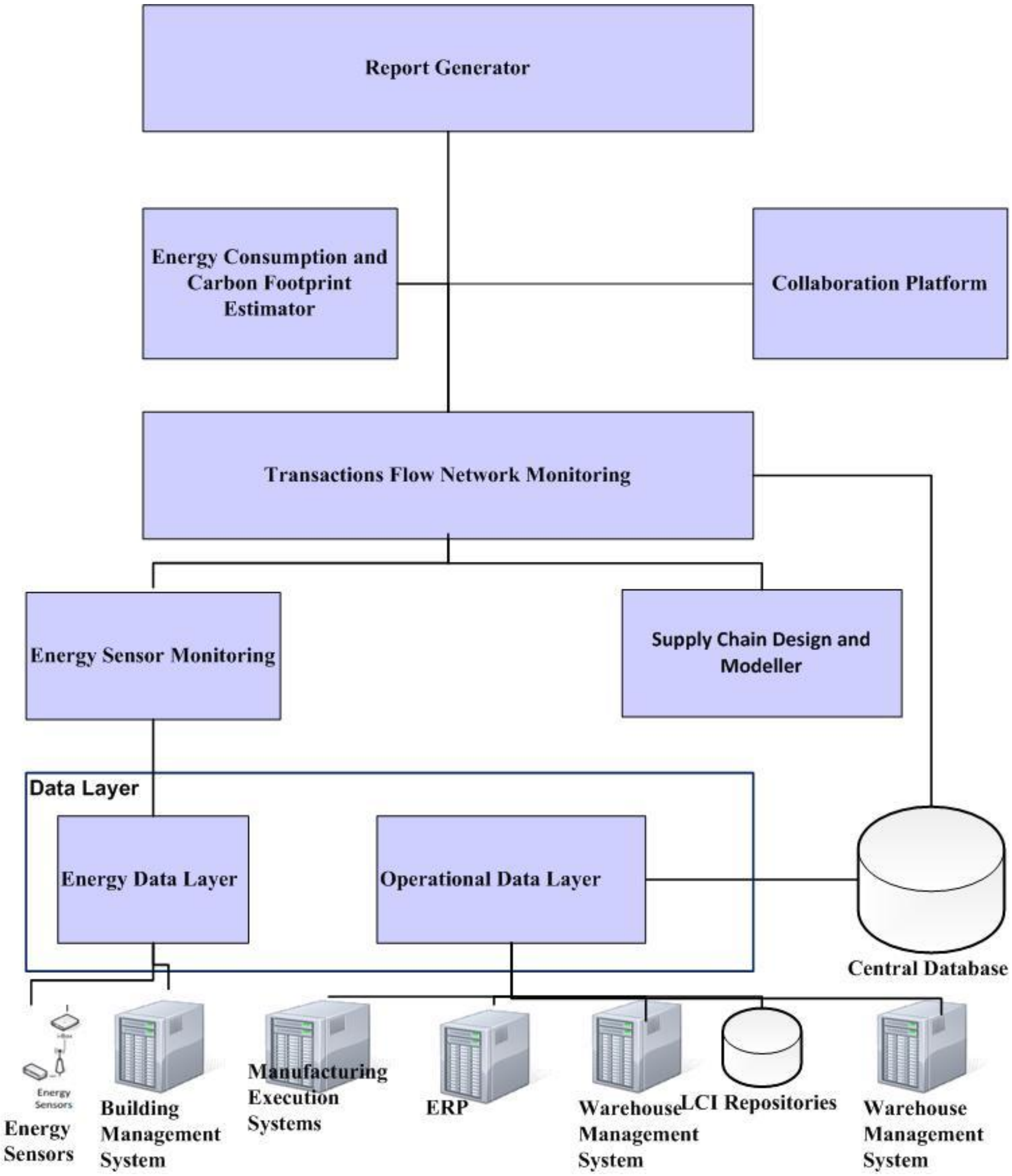


Figure 6.1: Architecture of the Energy and Carbon Management System Instantiation in Warehousing and Distribution

For brevity reasons, we present below only the list of the resulting components and their primary functional objectives. The detailed list of each component design principles is presented in Appendix E (Table E.1):

- The **Operational Data Layer** refers to the main data interface that will act as single point in the reception of the available data sources. Energy and Carbon Management is a data demanding process, which requires transactional and contextual data from various sources. Therefore, a component that collects, validates, cleans-up and identifies the relations among them is crucial for such an infrastructure. This component consists of two separate sub-components that will function independently of one another: the Data Layer energy sub-component and the Data Layer supply chain sub-component. The first handles the communication and synchronization with energy sensors and Building Managements Systems, while the second Operational Data Layer imports data coming from ERP, WMS and other corporate systems. Thus, this component handles all the transactional and contextual information required to monitor supply chain activities.

- The **Energy Sensor Monitoring** has the objective of collecting energy consumption data from the Energy Data Layer and implement a business logic for aggregating energy consumption at different levels of analysis and combining the energy data with the infrastructural information e.g. energy consumption per section. This component ensures the required energy consumption data will be available and covers in that way one of the prerequisites for the successful implementation of the industrial requirements. In terms of information flows, this component handles the environmental information flow and the contextual information flow (specifically associating energy power meters and products to specific warehouse and store sections).

- The **Supply Chain Design and Modeler** has the objective of designing the supply chain and providing all the required information regarding the supply chain objects of interest (e.g. node, product details, partners' details, etc.). In order to support energy and carbon management in the supply chain, the structure of the supply chain and the scope of monitoring need to be defined. Therefore, there is a need for a system component that will support the definition of the scope based on a user's existing supply chain settings. As contextual information is critical for the successful implementation of monitoring, this component also presents this information and lets the user update it. In terms of information flows, this component handles the contextual information flow.

- The **Transactional Flow Network Monitoring** refers to the monitoring and supervision of a set of supply chain processes e.g. distribution, ordering. This component is responsible for (a) monitoring the daily activities (shipments and storage), and (b) supporting the calculation of the required Key Performance Indicators (KPI's) for the different levels of analysis. In order to ensure the monitoring across the supply chain or even in warehousing and distribution processes, a component that is responsible to track the downstream of the supply chain and initiate the process of energy consumption and carbon footprint estimation is required. Moreover, it communicates with the collaboration platform in order to receive/ submit respective information from supply chain partners. In terms of information flows, this element handles the environmental information flow, transactional information flow, contextual information flow, environmental information flow and product environmental information flow, as it is a central component of the proposed architecture.

- The **Energy Consumption and Carbon Footprint Estimator** includes the business logic for aggregating and disaggregating energy consumption at various levels of analysis, transforming them into carbon emissions and then estimating the carbon footprint. This element incorporates allocation methodologies such as Life Cycle Assessment. More specifically, it (a) computes the carbon emissions of the activities (processes) of a supply chain (emissions from warehouses, stores, transportation and packaging materials), and (b) calculates the embodied carbon emissions of the products available in this supply chain by allocating the pre-computed emissions from activities to products. The carbon emissions are available: 1) per element of the supply chain, and 2) per product. The requirements impose the need for calculating impacts at different levels. However, the calculation and allocation of environmental impacts is a complex process that it is based on various methodologies; therefore, it is important that this logic is incorporated into a independent component, giving also the user the possibility to review and set the respective parameters used in the allocation logic. This element mainly handles the environmental information flow, but receives as input both contextual and transactional information.

- The **Report Generator** creates standard formatted reports that cover all the aspects of energy and carbon management in the supply chain (e.g. energy measurement, carbon footprint at different levels of analysis etc.). A dedicated reporting component is important in order for a user to perceive the system as one homogeneous entity. Presenting the outcomes of monitoring in a meaningful and user-friendly way is important for a user to understand a systems' value. Figure 5.3 depicts a view of the system reporting results.
- **Collaboration Platform** refers to the component that is responsible for maintaining the collaborative relationships between supply chain partners and facilitating data exchanges. Most importantly, it provides data to other elements. The efficient management of collaborations and the respective complexity is a critical point for the successful implementation of monitoring. Therefore, an independent component that supports it is needed. In terms of information flows, it handles all types of information flows that come from external partners.

Moreover, achieving energy and carbon management in the supply chain demands the integration with external resources. To better illustrate such requirement, we identify the (external) data interfaces required for the communication with existing systems (e.g. ERP, WMS, BMS, LCI) in terms of accomplishing collaboration and interoperability (as presented in Figure 6.2).

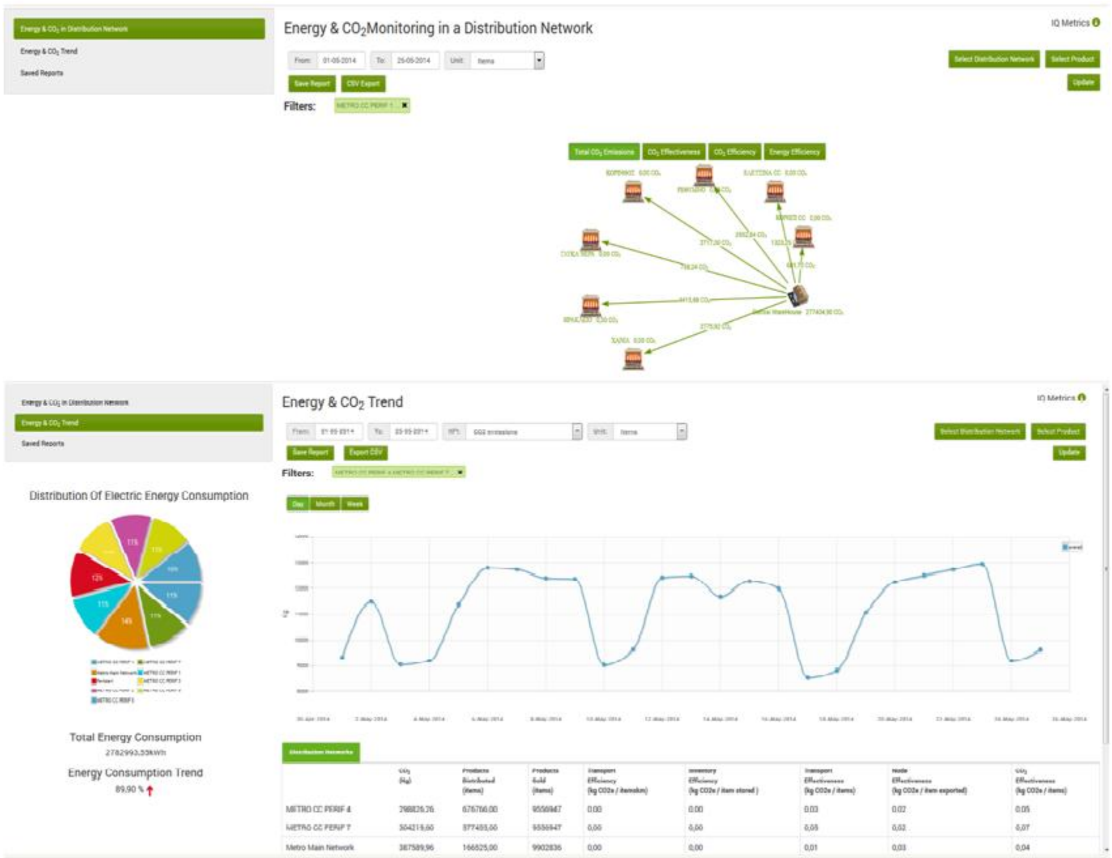


Figure 6.2: Energy and Carbon Management System Instantiation in Warehousing and Distribution

6.3 Demonstration and Evaluation

To probe and test the designed artifact in use and familiarize with any implementation issues, a system instantiation was developed and pilot tested. This system instantiation can be regarded as a basis of inquiry and interactive cognition. This means that it should had the properties required for its purposes and scope, and as few other properties as possible. To envision the three identified purposes and scope of energy and carbon management, we installed several pilot configurations described below. Since we defined the scope of demonstration, we investigated at first place the existence of the following systems:

a) ERP that handles the requests of customers, articles, quantities to be produced, stocks of raw materials and technical data sheets of fabrics,

b) WMS that aims to control the movement and storage of materials within a warehouse and process the associated transactions, including shipping, receiving, put away and picking as well as provide information regarding e.g. deliveries and inventories.

c) Energy Capturing Infrastructure or BMS that is responsible for collecting energy consumption data.

To build this pilot testing environment, we installed the prototype system, the required interfaces with existing systems and any energy capturing infrastructures (e.g. sensors) in real-world settings within two companies, a retailer and a food manufacturer and their supply chain partners in Greece and Italy. Moreover, a process for collecting, processing and validating the actual data that were necessary was deployed, following the data specifications discussed in Section 6.3. The implementation process followed is presented below:

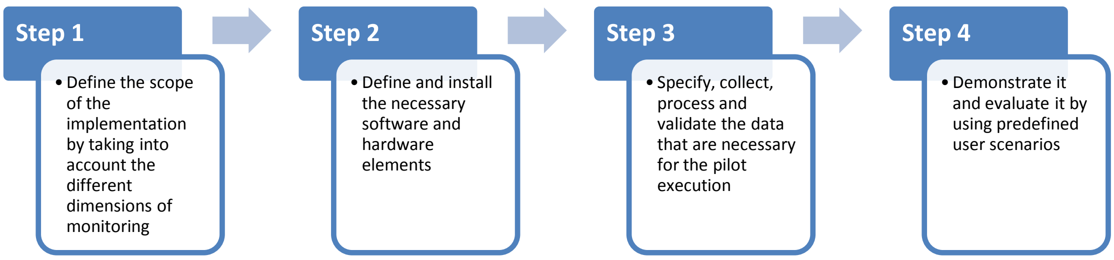


Figure 6.3: Implementation Process

During the initialization phase, some key elements were set such as the supply chain functional nodes, distribution networks and partnerships. The contextual information was sent only once during the initialization phase and then it was re-sent when updates were required. After discussions with the industrial users, it was decided to extract daily transactional data from their ERP and WMS systems respectively and upload them via FTP on the web platform for a period of twelve months. Moreover, any necessary software and hardware elements (e.g. energy sensors, interfaces) were installed.

This prototype can be regarded as a basis of inquiry and interactive cognition. This means that it should had the properties required for its purposes and scope, and as few other properties as possible. To envision the three identified purposes and scope of energy and carbon management, we installed several pilot configurations, one at a time.

The first pilot configuration captures energy consumption and carbon footprint per individual node of the supply chain. The retailers' central warehouse and three stores were chosen representing different environmental profiles (e.g. a store with old infrastructure, a conventional store and a store with new environmental-friendly infrastructure). Energy sensors were installed covering different sections in order to capture actual energy consumption data. In one of the stores this activity was replaced by integration with an existing building management system (BMS) that monitors energy consumption. Except for energy data, the rest data were already available in the retailers' internal ERP/ WMS systems.

The second configuration concerns the energy and carbon management during distribution activities. To do so, we selected two different distribution networks: a) the retailer's distribution networks from central warehouse to all stores, where the distribution is conducted by the retailer's own fleet of vehicles; and b) the supplier's distribution network from central warehouse to all the delivery points in a country, where the delivery is conducted via an external partner. In the case of the retailer’s distribution network, the retailer could provide all the transactional and contextual data required. Despite the fact that actual fuel consumption was not available, the vehicle fuel refills were available. This allowed getting an estimate of the average fuel consumption per vehicle and per type of route. In the case that the distribution process was supported by an external third party logistics provider (supplier's case), actual fuel consumption wasn't available at all, therefore industrial average's regarding fuel consumption were used for estimating environmental impacts. Moreover, information regarding the distribution process was not available and a set of assumptions was deployed (i.e. extracting information deliveries and delivery batches from invoice and route datasets).

The third configuration tries to capture the scope of managing energy and carbon information across the supply chain and at product level. To do so, a joined network extended from supplier’s warehouse to retailers’ stores was installed. The synchronization of the contextual information such as the volume and weight of products or boxes is a critical piece of information for calculating environmental impacts at product level. Therefore, much effort was put on creating a common master data catalogue where information regarding all products and their packaging was aligned. Moreover, semantical integration between the data received from the two supply chain partners was also essential. For example, the "shipment" data entity didn't represent the same type of information in the retailer's and the supplier's information systems. A shipment in the supplier's case shows the deliveries from a start point to their delivery destination. However, in the retailer's case, a shipment includes all the intermediate destinations and not just the final destination of a delivery.

Finally, in order to support energy consumption and carbon footprint at product level, there is also the need to receive data from external sources such as LCI repositories in order to calculate the environmental impacts of a product during its whole life-cycle. But, this information is available for a limited number of products. Moreover, the integration with existing LCI repositories is not trivial as they don't always provide interfaces to other systems and they do not usually provide open access. Moreover, the information that they provide is calculated with a specific methodology that limits its comparability and restricts its reusability in other calculations. Therefore, this kind of data wasn't used.

During the pilot testing, the system was also evaluated in order to explain whether the non-functional requirements are met. The non-functional requirements have been collected from the input and the discussion with the business partners and were based on the Standard ISO/IEC model, which defines quality standards by identifying a set of features and attributes that a generic software needs to have. Moreover, a further evaluation of the artifacts was conducted by selected employees working in our study Cases in order to gain feedback about the efficiency of the system. They interacted with the system by executed a set of pre-defined scenarios and then completed a questionnaire for evaluation purposes. The results are presented in Appendix F.

6.4 Findings for the Design and the Implementation

In the previous section, we presented in detail the instantiation of an ECMS in warehousing and distribution, the artifact architecture and its respective components and the actual context under which it was implemented. In this section, we provide empirical evidence on the main issues we came across during the demonstration, pilot testing and evaluation of the ECMS in the warehousing and distribution settings. These issues are related with the following aspects presented above a) Data quality and availability, b) Data capture and integration and c) Environmental Performance Metrics selection d) Collaboration and information sharing that are further elaborated below. Therefore, the existence and the integration of the aforementioned information flows has been the focus of this analysis, as this is a core consideration of such systems. Moreover, technical or process-related issues are further discussed. Insights on how these issues could be tackled are also provided. Evidently, these challenges reveal specific design and implementation principles to be implemented in order to ensure the efficacy of such systems in a real-world context. The design principles define what a system should provide in order to cover the requirements. The implementation principles concerned with the process of setting up and maintaining the proposed class of systems. The following key findings emerged from the demonstration, pilot testing and guided our effort to refine the design of an ECMS.

Therefore, these findings could become a guide towards the design and the implementation of ECMS in the Warehousing and Distribution. Note that we don't claim exhaustiveness.

More specifically, the various issues can be summarized in the following list:

- the environmental data availability
- the data quality and data inconsistencies
- the data granularity levels
- the complexity of integrating various types of data (e.g. energy consumption data with and warehousing and distribution data)
- technical integration issues and absence of automation mechanisms
- dependencies and coordination problems due to the need of aligning inputs from various supply chain partners
- the definition and selection of environmental and traditional performance measures
- collaboration issues and information sharing concerns

Below, we discuss each one of these findings and we conclude with a set of design and implementation principles guidelines that could be taken into account in order to design and implement an ECMS in the Warehousing and Distribution.

Environmental data availability

One of the main problems of implementing ECMS is that the existing information systems don't typically store non-traditional supply chain information, such as energy consumption and fuel consumption. This information is needed in order to calculate environmental impacts.

Companies keep aggregated information for energy consumption on a monthly period based on the electricity bills, or they manually record the energy consumption via physical audits. In these cases the installation of energy sensors in order to capture energy consumption was required. However, there are also some cases where they have already installed energy power meters or building management systems. In these cases, integration issues are raised up as many types of energy meters cannot interoperate with other information systems. In our cases, as discussed above, we covered all the aforementioned alternatives.

As the availability of the environmental information flow is a prerequisite for the implementation of an ECMS, the diversity and the limited environmental availability is an aspect that has affected the design of the ECMS and the respective data requirements. It affects the database schema. The ECMS manages both actual measurements of energy sensors and energy or fuel consumption based on secondary data and makes the respective calculations. A dedicated component for the management of actual energy consumption data captured by energy sensors was developed called as Energy Sensor Monitoring. As this component should be able to integrate with various sensors general standards regarding energy sensors were adopted.

Even more limited was the availability of fuel consumption data. Most of the firms are mainly interested in keeping fuel consumption only for accounting and cost monitoring purposes. Therefore, if they keep it, they usually store it expressed in cost or aggregated for a specific period of time, mainly for reporting purposes, and not per vehicle or vehicle type, as required for Energy and Carbon Management. The actual vehicle refills is available in limited cases. In our cases, we have either actual vehicle refills or none data. For the case where vehicle refills were available, a mechanism that calculates fuel consumption based on the invoices that are kept in ERP systems was developed. For the other case, industrial averages regarding vehicle fuel consumption based on their type were used and a configuration parameter defining data availability was incorporated as a basic parameter. Moreover, the information regarding the type of data that were used for the calculations should be presented in order the user to be informed about the type of environmental data used.

Therefore, the following design principles suggest ways to increase the availability of environmental data and use all the available environmental data.

Design Principles:

In the design phase of an ECMS in Warehousing and Distribution, the following design principles could be taken into account

a. The system should manage (collect, process and store) the various types of energy and fuel consumption e.g. both actual measurements of energy sensors and energy or fuel consumption based on secondary data in order to enable a company to implement energy and carbon management based on its current data availability levels.

b. The system should include configuration parameters referring to data availability in the components of an ECMS that are responsible for the data uploading and storing, for conducting the energy and carbon estimations and allocations and for managing and integrating all information flows in order to adopt energy and carbon management on a firm's data availability levels.

c. The system should implement mechanisms for producing environmental data based on secondary transactional data e.g. a mechanism for calculating fuel consumption based on the invoices could be used as an alternative source of information.

d. The system should implement general standards regarding energy sensors in order to facilitate the integration with existing energy sensors infrastructure if needed.

e. The system should implement an interface that will inform users about the environmental data used in the calculations ensuring data transparency.

Implementation Principles:

In the implementation phase of developing an ECMS, the following steps concerned with the process of setting up the system would ensure the requisite environmental information flows.

a. Define the type of energy and fuel consumption that should be collected and monitored and examine the environmental data availability.

b. Identify the technical infrastructures that will provide them (e.g. installed energy meters) or fuel consumption meters and examine if any infrastructure investment (e.g. power meters) is needed.

c. Define the process of retrieving data (e.g. what interfaces and how they should be developed, how often the data should be sent)

d. Define the configuration of the ECMS related to data availability

Data quality and data inconsistencies

The poor data quality (e.g. on product information and inventory levels) was identified as one of the main obstacles for the implementation of an ECMS. Even the more traditionally used transactional information such as inventories and deliveries was sometimes inaccurate e.g. negative values of inventory levels. However, the problem of poor data quality grows when we take into account packaging details such as the weight of products, the accurate weight and volume information that are taken into account by the most of the existing approaches for calculating environmental impacts.

During the pilot testing, we tried to restrain these problem by initially define an extended list of the data required and starting a process of mapping the existing with the required data. In cases of missing data, we define which of the system functionalities are eliminated and discuss if some of the missing data could be retrieved or produced in another way. More specifically, we choose to tackle the issue with packaging by following a data cleansing process of the provided weight and volume data. In collaboration with the users and by using data from both the retailer and the supplier, we compared, identified and corrected the products with wrong weights. For the missing weights or volumes, we produced estimated information, either by using secondary data from other sources or by estimating an average weight per product category.

Besides, there are a couple of inconsistencies and difficulties in transforming data in compatible terms. For example, it is rather hard to express the vehicle capacity: while vehicle capacity is commonly expressed in number of pallets, the transportation requests of stores are expressed in items and the relevant quantities. Thus, to express these two metrics in compatible terms, special approaches of translating the required products into number of fully-loaded pallets must be built. In addition, the dimensions (except for their weight) of these items should also be recorded. Currently, many firms keep only the deliveries that they conduct and not the actual route that was followed in order to ship products. In that case, a pseudo-route could be produced in order to simulate the actual delivery route.

Therefore, the following design principles suggest ways to tackle the poor and improve data quality and eliminate data inconsistencies.

Design Principles:

In the design phase of an ECMS in Warehousing and Distribution, the following design principles could be taken into account

a. The system should collect data that have been produced in a non-automatic way e.g. towards a user interface for uploading data that are kept in excel-like format

b. The system should deploy mechanisms that will transform the data in compatible forms e.g. comparative measurement units.

c. The system should deploy mechanisms and business logic that produce the missing data based on the existing ones e.g. the route through shipments.

d. The system should provide a data-cleansing mechanism that will validate and clean-up the data received in order to be integrative.

e. The system should provide a mechanism that will ensure that the received data are compliant to the data specification standard.

f. The system should inform a user regarding data quality e.g. towards a user interface in order to interpret the results in an accurate way.

Implementation Principles:

In the implementation phase of developing an ECMS, the following steps concerned with the process of setting up the system could be taken into account for tackling the poor data quality and inconsistencies:

a. Define the full data dataset required for the system to support the selected Energy and Carbon Managements scope, The data requirements should also specify details regarding data granularity level by taking into account the following dimensions: time, product, physical unit (e.g. store, warehouse, vehicle, shipment, production order, machine)

b. Examine whether the required data are available in the granularity level required and define the deficiencies in order to see if data deficiencies impact the provided system functionalities

c. Examine if the missing or incomplete data could be produced towards a non-automatic way and used as initialization data at the system set-up phase.

d. Produce a full dataset based on the available data quality and inconsistencies and validate it towards a test case scenario.

Data granularity levels

The specification of the required data granularity level is one of the other major issues that were raised in this context. Even when the data of the transactional and environmental information flows were available, they were usually available at different granularity levels. For example, the transactional data (e.g. inventory levels, deliveries, shipments) were kept on a daily basis. Moreover, there have been other cases where the deliveries and the shipments have or don't have details regarding the departure and arrival time. Environmental data can be either kept on a highly aggregated level, e.g. monthly, or can be too detailed, as energy sensors can record energy consumption even on few seconds basis. These different granularity levels were also one of the main obstacles of integrating the various information flows.

Defining the right data granularity level based on the available information flows ensures that the various information flows can be integrated. In our cases, we concluded that collecting and aggregating information on a day level can be an adequate granularity level of analysis that ensures both the applicability of an ECMS and also the meaningfulness of the results.

By taking into account the aforementioned constraints and also the initial requirements, we concluded that the granularity level was one of the basic parameters of the ECMS and it was incorporated in the Data Layer components that is responsible for the data uploading and data storage processes, the Energy Consumption and Carbon Footprint Estimator component that estimates the energy and carbon emissions and the Transactions Flow Network Monitoring that handles all the information flows.

Therefore, the following design principles suggest ways to ensure the same granularity levels in the received data.

Design Principles:

In the design phase of an ECMS in Warehousing and Distribution, the following design principles could be taken into account

a. The system should incorporate the data granularity as a basic configuration parameter in the components of an ECMS that are responsible for the data uploading and storing, for conducting the energy and carbon estimations and allocations and for managing and integrating all information flows.

b. The system should provide mechanisms that will transform data in the same granularity level e.g. mechanisms for aggregating energy consumption data on a day granularity level in order to be the same with inventories granularity levels

Implementation Principles:

In the implementation phase of developing an ECMS, the following steps concerned with the process of setting up the system would ensure the same granularity levels.

a. Examine the granularity levels of the required data that defined in the specification of data requirements for an ECMS

b. Define the granularity levels by taking into account the available granularity levels but also other aspects such as the objective of energy and carbon management or the trade-off between the value of detail and cost of collecting, processing and keeping detailed information

Complexity of integrating various types of data (e.g. energy consumption data with and warehousing and distribution data)

One of the major issues that were confronted was the complexity of integrating the various information flows. The aforementioned problems were merely responsible for this problem as the integration of the various flows required a common granularity level, a complete and accurate dataset and the availability of all the data. During the integration process, the comparability of the results should also be taken into account. For example, we could not compare the environmental impact of two routes if we have used different allocation parameters e.g. weight, volume, and item. Therefore, except from taking the aforementioned actions, an adaptable logic of integrating the various flows and allocating the environmental impacts at different levels of analysis has been deployed in our case and was the main responsibility of the Energy and Carbon Estimator Component. The logic initially examines the data availability and presents a set of information availability measures. Then, the user uses this information and defines some parameters and the respective computation logic of the environmental impacts is applied.

Therefore, the following design principles suggest ways to address the integration of the various data types

Design Principles:

In the design phase of an ECMS in Warehousing and Distribution, the following design principles could be taken into account

a. The system should provide an adaptable logic of calculating and allocating environmental impacts at various levels of analysis by taking into account data granularity level, data accuracy and the availability of all data.

b. The system should inform the user about the allocation logic or the standard implemented in order to enable him to compare and interpret the results.

Implementation Principles:

In the implementation phase of developing an ECMS, the following steps concerned with the process of setting up the system would ensure the integration of the various information flows.

a. Defining the parameters that will configure the calculation and allocation logic of the environmental impacts by taking into account the following aspects, data granularity level, data accuracy and the data availability.

Technical integration issues and absence of automation mechanisms

Except from the data related issues that have been mainly discussed above, many technical issues should also be addressed. Starting from the environmental data, the integration with existing BMS and energy sensors and the retrieval of energy consumption data was a demanding process. It required not only the development of interfaces but also the development of mechanisms that ensure that we continually received the energy data. Moreover, environmental data was also recorded by using spreadsheet-like solutions and the integration and retrieval of environmental data should be automated. Automation was a difficult task in this case, as these data were not produced daily and a more sophisticated way of calculation should be developed; e.g. a mechanism that calculates fuel consumption based on the invoices that are kept in ERP systems was developed.

However, the retailer had a newly developed and installed WMS that was keeping information regarding all movements in the warehouse, the distribution process and movements in the store. It had already a well organized IT department and it had run various IT projects in the last few years. Therefore, the integration with the new system was easier and the data quality was ensured after few rounds of interactions.

Therefore, the following design principles suggest ways to facilitate the technical integration and automation.

Design Principles:

In the design phase of an ECMS in Warehousing and Distribution, the following design principles could be taken into account:

a. The system should use technologies that support componentization and can improve the reusability, interoperability and integration of the systems such as, object-oriented design, web services, eXtensible Markup Language (XML), and service-oriented architecture.

b. The system should use standards for information sharing among supply chain partners in order to support Energy and Carbon Management in the Supply Chain.

c. The system should provide various interfaces options in order to automate data retrieval from various systems e.g. ftp, web-services

Implementation Principles:

In the implementation phase of developing an ECMS, the following steps concerned with the process of setting up the system would facilitate the technical integration and automation.

a. Define the existing systems with which the ECMS should interact in order to retrieve data in an automated way

b. Investigate the existing level of automation and define the way and the technologies that the systems will interact e.g. interfaces, web services

c. Investigate the existing level of information exchange and try to leverage existing information exchange relationships.

d. Define the effort needed for developing automation mechanisms and decide if automation is suggested e.g. if data are required only at system set up phase an automation process may be skipped

Dependencies and coordination problems due to the need of aligning inputs from various supply chain partners

The implementation of ECMS across the supply chain, where collaboration among different partners is needed, increases the complexity due to the various flow dependencies and coordination problems. These coordination problems were mainly because suppliers and retailers used their own internal codes for describing the contextual information flow e.g. products, partners, facilities, vehicles. For example, even if a product has its own barcode that remains the same across the whole product lifecycle, supplier and retailer prefers not to keep it and they use an internal product code called Stock Keeping Unit (SKU). Moreover, the different partners expressed the measurements units used for packaging e.g. weight in kg and some other in gr. In order to tackle the aforementioned issues, a specific component responsible for supporting the coordination of the different partners' information flows was developed called collaboration platform. Moreover, a master data alignment feature of the relevant contextual information was designed. These feature identified and presented for example a list of products that cannot be mapped in both supplier and retailer catalogue.

Therefore, the following design principles suggest ways to facilitate the inputs alignment from various supply chain partners.

Design Principles:

In the design phase of an ECMS in Warehousing and Distribution, the following design principles could be taken into account:

a. The system should provide master data alignment mechanisms e.g. of products in order to support the traceability in the supply chain.

b. The system should provide mechanisms that support the coordination of all workflows e.g. orders, deliveries, and shipments of the different partners in order to enable energy and carbon management in the supply chain.

Implementation Principles:

In the implementation phase of developing an ECMS, the following steps concerned with the process of setting up the system would facilitate the inputs alignment from various supply chain partners.

a. Define the workflows that should be tracked (e.g. shipments, products, orders) and then examine if the available workflows should be synchronized.

b. Define the alignment process that should take place either as part of the set-up phase or regularly. For example, product master data alignment process across the supply chain involving supply chain partners should take place at the set-up phase of an ECMS.

Definition and selection of environmental and traditional performance measures

Despite the fact that energy and carbon management has a growing interest, no standardized Key Performance Indicators could be calculated on a detailed basis and more specifically on a daily basis in our case. Therefore, one of the main issues that were raised was to define the indicators that should be calculated. These performance indicators should cover both the traditional operational aspects and the environmental ones. Moreover, the need of using integrated indicators that incorporate both environmental and operational aspects came up. In our case, we adopted the Sustainability Measures for Logistical Activities that were suggested by the 2016 KPI team (The Consumer Good Forum, 2012) as they try to cover environmental and operational aspects and incorporate them into integrated indicators. However, the system should give the ability to a user to expand the specific list of KPIs and even to create their own set KPIs.

Therefore, the following design principles suggest ways to define and select energy and carbon indicators.

Design Principles:

In the design phase of an ECMS in Warehousing and Distribution, the following design principles could be taken into account

a. The system should implement a list of various assessment methodologies and energy and carbon management standards.

b. The system should provide a list of a list of various energy and carbon indicators.

c. The system should provide a user the ability to create new energy and carbon indicators if the data are available

Implementation Principles:

In the implementation phase of developing an ECMS, the following steps concerned with the process of setting up the system would define the energy and carbon indicators.

a. Select the energy and carbon indicators that should be monitored and create new ones if needed in order to support decision making processes and the implementation of sustainable supply chain practices

b. Select the assessment methodology and energy and carbon management standards that should be followed in order the outcomes to be comparable.

Collaboration Issues and Information Sharing Concerns

Collaboration is the driving force behind effective supply chain management, which is usually described as the result of trust and commitment between two trading parties. However, the collaboration culture on environmental issues is still in its infancy and the mutual benefits are still underexplored. Therefore, the clear context of collaboration should be defined e.g. benefits, cost of collaboration, data exchanged and be depicted in the system configurations. The discrimination of collaboration in various levels could also facilitate the initiation of such efforts. Another major challenge in this context refers to the comparability of the various energy and carbon indicators due to diversity in the used energy and carbon calculation and allocation methods. This challenge could be addressed for example by defining and deploying a global energy and carbon calculation and allocation method.

Information sharing concerns are one of the most discussed issues in the supply chain and information systems literature. However, these concerns tend to increase in the case of the ECMS due to their data intensive requirements and their sensitivity. For example, some companies don't want to disclose their environmental information as they think that if they reveal information regarding bad environmental performance this could be used during the negotiation process by their supply chain partners. Moreover, in the case of 3PL companies, environmental information sharing could also be a way of sharing information about costs with your clients. These concerns could be limited by defining a minimum required dataset or even sharing aggregated high level performance indicators.

In our case, the long collaboration between the two partners has been an important facilitator for implementing an ECMS due to the mutual trust and also the established information sharing processes. Moreover, the ECMS was designed in such way in order to provide different levels of collaboration that will support the gradual engagement of supply chain partners to energy and carbon management and to differentiate information sharing requirements based on the level of collaboration. These extra features facilitate the implementation of the ECMS by diminishing information sharing and privacy concerns.

Therefore, the following design principles suggest ways to facilitate collaboration, support information sharing and eliminate information sharing concerns.

Design Principles:

In the design phase of an ECMS in Warehousing and Distribution, the following design principles could be taken into account

a. The system should provide a feature that the definition of new partnerships and the terms of this collaboration and the management of existing ones;

b. The system should provide features that will enable various types of collaboration and information exchange levels

c. The system should provide features that ensures data privacy e.g. security protocols implemented

d. The system should provide data exchange mechanisms in order to facilitate information sharing

e. The system should incorporate a calculation method that supports monitoring across supply chain that will examine and make sure that the collaborative partners have adopted compatible LCA measurement model(s), therefore the calculation of direct and indirect emissions are managed uniformly.

Implementation Principles:

In the implementation phase of developing an ECMS, the following steps concerned with the process of setting up the system would enable collaboration and information exchange

a. Define the terms of collaboration by making clear the mutual benefits and the effort needed for establishing the collaborative relationship

b. Define the various levels of collaboration in order to enable supply chain partners to engage gradually to Energy and Carbon Management practices

c. Define the information sharing requirements and differentiate them based on the level of collaboration

d. Leverage already established relationships and information sharing mechanisms

6.5 Capturing Knowledge for Impact gained from Artifact Demonstration

Energy and Carbon Management is one of the prominent issues towards the development of environmentally sustainable supply chains (Seuring & Müller, 2008). Within this context, ECMS are recognized as a key resource to support organizations in the development of sustainable supply chains (Dao et al., 2011; Melville, 2010) by measuring energy and carbon emissions and enabling energy and carbon management. More specifically, ECMS collect, integrate and calculate energy and carbon emissions in various levels of analysis promising to increase awareness and visibility of energy consumption and carbon emissions in the supply chain. Moreover, ECMS are expected to impact the enablement of environmental sustainable supply chains by supporting environmental-aware decision-making in the supply chain (Butler, 2011) and sustainable supply chain practices implementation (Seidel et al., 2013). The ultimate goal of this section is to provide some first empirical evidence on how ECMS impact the implementation of environmentally sustainable supply chains and to highlight how the data collected by an ECMS and the functionalities provided by them could be leveraged in order to support energy and carbon management, and environmental-aware decision-making and sustainable supply chain practices implementation. In that way, we are going to provide evidence on the testable propositions discussed in Section 4.3.

In a nutshell, the ECMS collect energy consumption and fuel consumption data (e.g. from energy sensors, energy management systems, building management systems) and report them even in real-time, collect other traditional supply chain related data (production and distribution data) from existing systems (e.g. ERP, MES, WMS) and integrate them with the energy and carbon ones in order to calculate environmental and traditional supply chain performance indicators. Moreover, in the context of supply chain, they support the collaboration of various supply chain partners and the sharing of information extending in that way energy and carbon management in the whole supply chain.

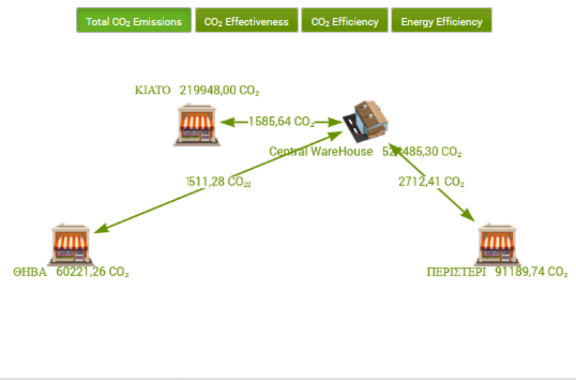
Below, we present a series of scenarios of energy and carbon management that were defined based on the purpose and scope of energy and carbon management (Section 4.2) and the interaction with the users during the system demonstration and evaluation, some exemplary relevant questions and how the ECMS impact their implementation by collecting the data required and providing various KPIs. More specifically, we provide empirical evidence on how the ECMS contribute on answering these specific questions by taking into account the KPIs, data and system functionalities required to support them. We don't intend to deploy an exhaustive list of questions and scenarios but to provide some proof-of-concept examples as they came during the evaluation phase with the users.

Table 6.5: Energy and Carbon Management Scenarios/ Examples

Energy and Carbon Management Scenarios/Examples	**Exemplary Decisions/ Questions to be answered**	**KPIs Required**	**Data Required and Granularity Level**	**ECMS Role**
Manage energy and carbon emissions of the retailer's three stores with different environmental profile and compare them	• Which is the energy and carbon efficiency of the stores sections? • Which is the energy and carbon efficiency of the stores? • Which is the more inefficient store in terms of energy consumption and carbon emissions? • Which is the energy and carbon efficiency of a specific product/product category in a store? • How much the energy and carbon efficiency of a specific product/product category differs among the various stores?	• The KPIs required and their respective level of analysis is defined at Table 6.6 including e.g. in Total Energy Consumption, Energy efficiency (KWh/m^2), CO2e-effectiveness, Inventory Level • The KPIs are required to be calculated on a daily basis except from the Energy consumption that should be also available in a hourly basis	• The data required are defined at Table 6.4 (Managing energy and carbon information for warehousing Column). • The contextual data should be collected once at the initialisation phase. • The transactional and environmental should be collected daily.	• The ECMS collects the energy consumption data (e.g. from the new installed energy sensors and the existing building management systems) by using **Energy Data Layer** and **Energy Sensor Monitoring** and its respective interfaces. • The ECMS collects the rest data from the retailers' internal ERP/ WMS systems by using **Operational Data Layer**. • The ECMS through **Transactions Flow Network Monitoring** component integrate the data and calculates the KPIS required. For the calculations, it uses the **Energy Consumption and Carbon Footprint Estimator** component where the business logic for aggregating and disaggregating anticipated energy consumption, transforming them into carbon emissions and then estimating the carbon footprint is nested. • The ECMS towards the **Supply Chain Design and Modeller** supports the selection of the three specific stores and the design of a distribution network that includes only them. • The calculated KPIs for the specific stores are presented towards the **Report Generator**. Figure 6.4 shows the outcome of this example.

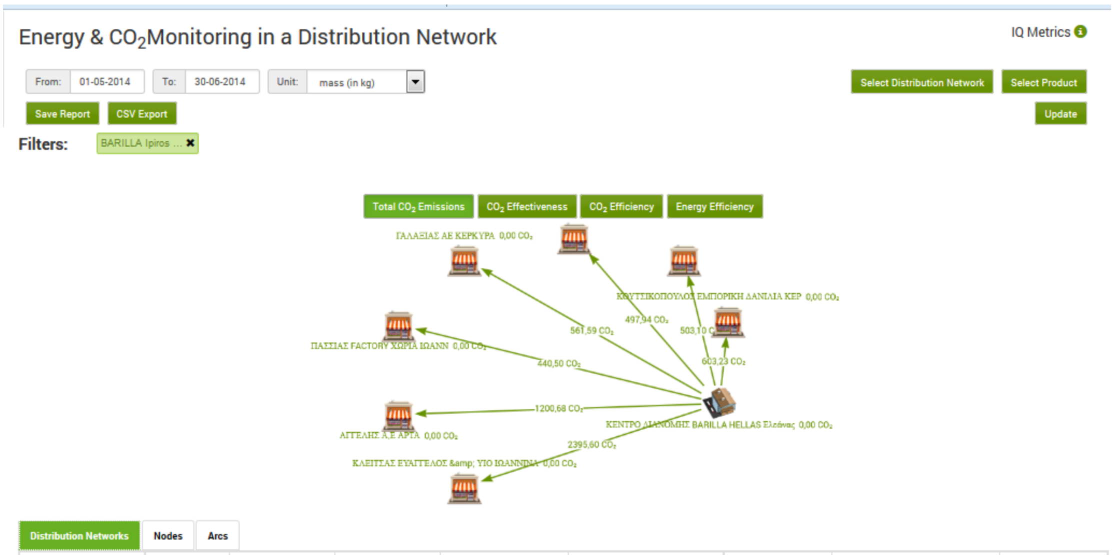
Managing energy and carbon information for distribution activities and comparing distribution networks with different distribution policy	• Which are the energy consumption and carbon emissions at the retailer's distribution networks from central warehouse to all stores, where the distribution is conducted by the retailer's own fleet of vehicles? • Which are the energy consumption and carbon emissions at the supplier's distribution network from central warehouse to all the delivery points in a country, where the delivery is conducted via an external partner? • Which route is the most inefficient in terms of energy consumption and carbon emissions? • Which is the energy and carbon efficiency of a specific product/product category in distribution network? • How much the energy and carbon efficiency of a specific product/product category differs among	• The KPIs required and their respective level of analysis is defined at Table 6.3. including e.g. in Total Energy consumption, Energy efficiency (KWh/m2), CO2e - effectiveness, Vehicle Fill Rate • The KPIs are required to be calculated on a daily basis when applicable	• The data required are defined at Table 6.4 (Managing energy and carbon information for distribution activities Column). • The contextual data should be collected once at the initialisation phase. • The transactional and environmenta l should be collected daily.	• The ECMS supports this example by following the process and using the components described above. As there is no need for energy consumption data in this case, both **Energy Data Layer** and **Energy Sensor Monitoring** aren't needed. The fuel consumption data are produced by using secondary data comes from operational data with the support of the **Operational Data Layer**. • Figure 6.5 shows the outcome of this example

	the various distribution networks?			
Managing energy and carbon information across the supply chain at a joined network extended from supplier's warehouse to retailers' stores	• Which are the energy consumption and carbon emissions at the joined supply chain network? • Which routes are the most inefficient in terms of energy consumption and carbon emissions? • Which are the energy consumption and carbon emissions across a product life cycle at a joined network extended from supplier's warehouse to retailers' stores? • Which distribution networks are the most inefficient in terms of energy consumption and carbon emissions for products?	• The KPIs required and their respective level of analysis is defined at Table 6.7 and Table 6.3 including e.g. in Total Energy consumption, Energy efficiency (KWh/m2), CO2e effectiveness, Inventory Level, Transport _CO2_effectiveness • The KPIs are required to be calculated on a daily basis when applicable • Special emphasis has been given on KPIs on product level	• The data required are defined at Table 6.4 (Managing energy and carbon information across the supply chain Column). • The contextual data should be collected once at the initialisation phase. • The transactional and environmental should be collected daily.	• The ECMS supports this example by following the process and using the components described in the previous example. As the supply chain network is extended across the supply chain and includes two partners, collaboration and information is a prerequisite in to order to enable it. Therefore, Collaboration Platform is used in order to handle partnerships and information exchange. • Figure 6.6 shows the outcome of this example.



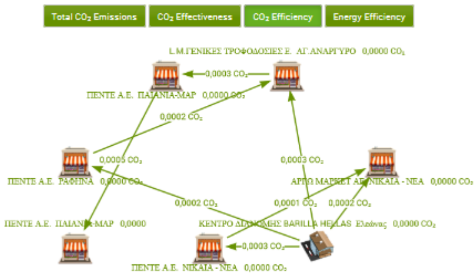
	Kwh (Kwh)	CO_2 (Kg)	Products Stored (mass (in kg))	Products Sold (mass (in kg))	Energy Efficiency (Kwh/m2)	Area (m2)	Space efficiency (kg CO2e / m2)	Inventory efficiency (kg CO2e / kg stored)	Node Effectiveness (kg CO2e / kg)
Metro Main Network : ΘΗΒΑ	60047,13	60221,26	101769,18	281784	1,00	1359,40	1,01	0,0130	0,1890
Metro Main Network : ΚΙΑΤΟ	219312,00	219948,00	0,00	142772	3,14	1269,00	3,15	0,0000	1,0920
Metro Main Network : Central WareHouse	522968,70	524485,30	6243841,69	20332487	0,29	41679,05	0,29	0,0020	0,0250
Metro Main Network : ΠΕΡΙΣΤΕΡΙ	90926,05	91189,74	0,00	358191	1,56	1322,12	1,57	0,0000	0,2310

Figure 6.4: Manage energy and carbon emissions of the retailer's three stores with different environmental profile and compare them



	CO_2 (Kg)	Products Distributed (mass (in kg))	Products Sold (mass (in kg))	Transport Efficiency (kg CO2e / kgkm)	Inventory Efficiency (kg CO2e / kg stored)	Transport Effectiveness (kg CO2e / kg)	Node Effectiveness (kg CO2e / kg exported)	CO_2 Effectiveness (kg CO2e / kg)
BARILLA Ipiros	25566,75	169379,68	180332	0,02	0,00	0,02	0,00	0,32

Figure 6.5: Managing energy and carbon information for distribution activities and comparing distribution networks with different distribution policy



Distribution Networks | Nodes | Arcs

	CO_2 (Kg)	Distance travelled (Km)	Products Distributed (mass (in kg))	Transport Efficiency (kg CO2e / kg)	Transport Effectiveness (kg CO2e / kgkm)
BARILLA Collaboration (local) network : ΚΕΝΤΡΟ ΔΙΑΝΟΜΗΣ BARILLA HELLAS ➔ ΠΕΝΤΕ Α.Ε.	709,4590	719,1630	33885,4150	0,0003	0,0209
BARILLA Collaboration (local) network : ΚΕΝΤΡΟ ΔΙΑΝΟΜΗΣ BARILLA HELLAS ➔ L.M.ΓΕΝΙΚΕΣ ΤΡΟΦΟΔΟΣΙΕΣ Ε.	140,9820	141,4700	7071,1520	0,0003	0,0199
BARILLA Collaboration (local) network : ΠΕΝΤΕ Α.Ε. ➔ ΠΕΝΤΕ Α.Ε.	75,1870	81,5760	7326,8380	0,0005	0,0103
BARILLA Collaboration (local) network : ΠΕΝΤΕ Α.Ε. ➔ ΑΡΓΩ ΜΑΡΚΕΤ ΑΕ	0,5520	2,8620	9635,3540	0,0001	0,0001
BARILLA Collaboration (local) network : ΠΕΝΤΕ Α.Ε. ➔ L.M.ΓΕΝΙΚΕΣ ΤΡΟΦΟΔΟΣΙΕΣ Ε.	34,2460	33,7440	4469,9200	0,0002	0,0077
BARILLA Collaboration (local) network : L.M.ΓΕΝΙΚΕΣ ΤΡΟΦΟΔΟΣΙΕΣ Ε. ➔ ΠΕΝΤΕ Α.Ε.	47,5740	44,6510	3756,4770	0,0003	0,0127
BARILLA Collaboration (local) network : ΚΕΝΤΡΟ ΔΙΑΝΟΜΗΣ BARILLA HELLAS ➔ ΠΕΝΤΕ Α.Ε.	130,9640	123,0000	25890,1480	0,0002	0,0051
BARILLA Collaboration (local) network : ΚΕΝΤΡΟ ΔΙΑΝΟΜΗΣ BARILLA HELLAS ➔ ΑΡΓΩ ΜΑΡΚΕΤ ΑΕ	394,6240	394,8000	20124,0010	0,0002	0,0196

Figure 6.6: Managing energy and carbon information across the supply chain at a joined network extended from supplier's warehouse to retailers' stores

Aided by the energy and carbon management process presented above and by leveraging the data and the KPIs calculated and presented above, ECMS could support environmental - aware decision-making in the supply chain. Some indicatively types of decisions that came from our cases and could be supported are the following:

- Reengineering the warehouse/ store in terms of storage infrastructure, for example reduce the number/ capacity of refrigerators and air-conditioners, according to the identified inefficient warehouse/ store sections in terms of energy.
- Changing the store's outlet as such, the energy is better allocated between the environmentally - inefficient product/ product categories.
- Reengineering the stores' ordering strategy in terms of products, quantities with the purpose to minimize the time the products spend in storage and absorb energy e.g. change the order frequency.
- Reengineering the distribution processes in the supply chain according to the obtained energy profile of the current supply chain arcs and adopting more environmental friendly routes e.g. adopt collaborative distribution
- Focusing on products that appear to have poor environmental performance and take corrective actions and
- Selection of products to provide to the consumers their energy profiles in order to capture their interest and increase the company's environmental profile in their mind.
- Redesign of a supply chain network by building a new distribution center/warehouse
- Packaging decisions regarding for example the height of the pallet

Moreover, environmentally sustainable supply chain practices could be developed by leveraging the data and the KPIs calculated and presented in Table 6.5. In our cases for example, it supports the collaborative distribution supply chain practice by supporting the collaboration with the involved supply chain partners and calculating the required KPIS. More specifically, the retailer collaborates with its suppliers for the distribution of their products. More specifically, the retailer's vehicles are responsible for replenishing the stores of the supermarket network, are also while at their way back; they responsible for visiting the suppliers for carrying products back to the central warehouse. The Collaborative Distribution example involved eight suppliers' central warehouses and the retailer's central warehouse and different types of stores (105 in total). The ECMS collects and integrates data from the various resources (e.g. Retailers and Suppliers ERP, WMS) and calculates the following KPI's that are required:

- TotalRoutes: The total routes travelled over the considered time horizon
- TotalWeightDelivered: The total weight of the products delivered to the stores over the time horizon
- TotalWeightPicked-Up: The total weight of the products picked-up from stores (returns) and suppliers over the time horizon
- TotalDistance: The total distance travelled by the vehicles over the time horizon
- Fill Rate: the average capacity utilization (based on the transported pallets) of the vehicles leaving the warehouse (beginning of the route)
- TotalTnKilometers: The total ton x kms travelled by the vehicles
- Total Vehicles Used: The aggregated vehicles used over the time horizon
- TotalPalletstDelivered: The total pallets delivered to the stores over the time horizon
- TotalPalletsPicked-Up: The total pallets picked-up from stores (returns) and suppliers over the time horizon
- FuelPerTnKm: The quantity of fuel consumed per tn x km travelled and
- CO2e/ km: The total CO2 emissions per km travelled.

7 DISCUSSION AND CONCLUSIONS

7.1 Introduction

This final chapter discusses the main outcomes of this research. Elaborating on the research outcomes, we detail and discuss the theoretical contribution and the practical implications of this research in the following paragraphs. At the end of this chapter, the research limitations are pointed-out and avenues for further research are recommended.

7.2 Research Outcomes

This research journey began with the aim of advancing the understanding of "how" to design and implement an energy and carbon management system in the supply chain and shedding light on its impact as well as on the development of environmentally sustainable supply chains.

More specifically, the two following questions have been addressed:

- Q1. What is the design of energy and carbon management systems in the supply chain?
- Q2. How do energy and carbon management systems impact the development of environmentally-sustainable supply chains?

Initially, we reveal the need of an emerging class of information systems focusing on the energy and carbon management, called Energy and Carbon Management Systems (ECMS). These systems aim to support energy and carbon management in the supply chain and enhance decision-making and the implementation of sustainable supply chain practices. According to Melville & Whisnant, (2014), an ECMS is defined as "a type of enterprise information system that takes as inputs various types of environmental data (e.g., electricity and fuel use, furnace combustion, emission factors, employee commuting, and air travel), processes that data into usable information, (e.g., megajoules of energy, GHG emissions), and provides enhanced functionality (e.g., automated reporting, managerial dashboards, supply-chain analytics, and workflow management)." More specifically, these systems should be able to capture energy and carbon related information from energy consumption measurement infrastructures, to integrate and interoperate with a company's existing enterprise systems (e.g., ERP, WMS, MES), to interpret and integrate the data received from various sources, to exchange data with the enterprise systems of supply chain partners and support decision making in the supply chain.

Considering the above, we employed the Design Science research approach as methodological backbone. The final main outcomes of this thesis include:

- an ECMS artifact
- an IS Design Theory for ECMS that prescribes this new class of information systems and
- empirical evidence that reveals the impact of ECMS on the development of environmentally sustainable supply chains, by supporting energy and carbon management; environmental-aware decision-making; and sustainable supply chain practices.

However, by conducting each on the various steps that Peffers et al., (2007) proposed, we conclude with several intermediate results that also contributed to the development of the proposed artifact and to the systematical formulation of the basic components of the IS Design Theory.

Starting from the definition of the purpose and scope of energy and carbon management in the supply chain, an ECMS should support multiple “views” that allow a diverse and flexible use of energy and carbon management. Therefore, **the first outcome** is a set of energy and carbon management dimensions in the supply chain that extends from the supplier of raw materials up to the point of sales, where customers buy the final products. Each one of these dimensions is also characterized by its respective supply chain hierarchy levels and the respective Key Performance Indicators.

As our study aims to contribute to the design of an ECMS focusing on supply chain settings, a comprehensive and flexible blueprint of how information is organized and managed is required. Therefore, the **second outcome** includes a detailed list of data requirements that cover various aspects, such as time, product, physical unit (e.g. store, warehouse, vehicle, shipment, production order, machine), source. Moreover, we categorize this detailed list in four abstract groups. We use the term “information flows” to refer to these four groups of information flows.

Having defined the purpose and scope of energy and carbon management, we proceed with the examination of how information systems support such management. As such, we propose a set of design requirements (**third outcome**) from justificatory knowledge, including both literature, kernel theories and practitioners insight. These requirements give guidance to the subsequent specification of the design. During the formulation of the design requirements, special emphasis has been given to cover two important aspects of energy and carbon management: data and KPIs. Our aim is not to present the exhaustive set of design requirements for an ECMS, but rather to outline some essential requirements for these systems and demonstrate the applicability of design theory.

ECMS are expected to enable environmental sustainable supply chains by supporting energy and carbon management, environmental-aware decision making and sustainable supply chain practices implementation. Drawing on justificatory knowledge, we formulate three testable propositions (**fourth outcome**) in order to explore if the proposed design supports energy and carbon management, environmental-aware decision making and sustainable supply chain practices implementation. As such, we provide empirical evidence and shed light on the role of ECMS on supporting such initiatives. .

In order to cover the design requirements, we proceed with tracing a set of general system components that should be included in an ECMS. Special emphasis is given on the integration of the various information flows, as it is a prerequisite for most of the requirements and should be addressed by most of the components. Therefore, we propose a set of mandatory components that cover the requirements related to both manufacturing and supply chain by integrating the respective information flows and incorporating them in a conceptual high-level architectural framework for an ECMS. This architectural framework aims to specify in a more abstract level the components that this new class of information systems requires (**fifth outcome**). This architectural framework and the respective components are further elaborated on design principles that should guide the design and implementation of energy and carbon management systems (**sixth outcome**).

While the proposed architectural framework provides a general blueprint of a system’s design, the appearance of a corresponding concrete IT artifact is dependent on the context in which it is instantiated. For example, the instantiation of the components (i.e., Energy Consumption and Carbon Footprint Estimator, Data layer) is highly dependent on the context of the applied system. Data Capturing, Allocation methodology and KPIs, for example, will differ from those that are useful for product level monitoring. Likewise, different application settings might require different types of data (other file formats) or different external data sources (e.g., domain-specific databases). Moreover, even in a given context, the system instantiation will certainly evolve over time. When the system's knowledge base populates with new data, new KPIs and new granularity levels are needed to support energy and carbon management. Therefore, we instantiate the architectural framework in the two cases of manufacturing and warehousing and distribution separately and we develop two different artifacts (**seventh outcome)**. The ultimate goal is to validate the proposed architectural framework of an ECMS and conclude that the design principles arise sufficiently consistent across different contexts and cases. Below, we provide the two exemplary instantiations of these systems in order to highlight their similarities and their differences (Figure 7.1)

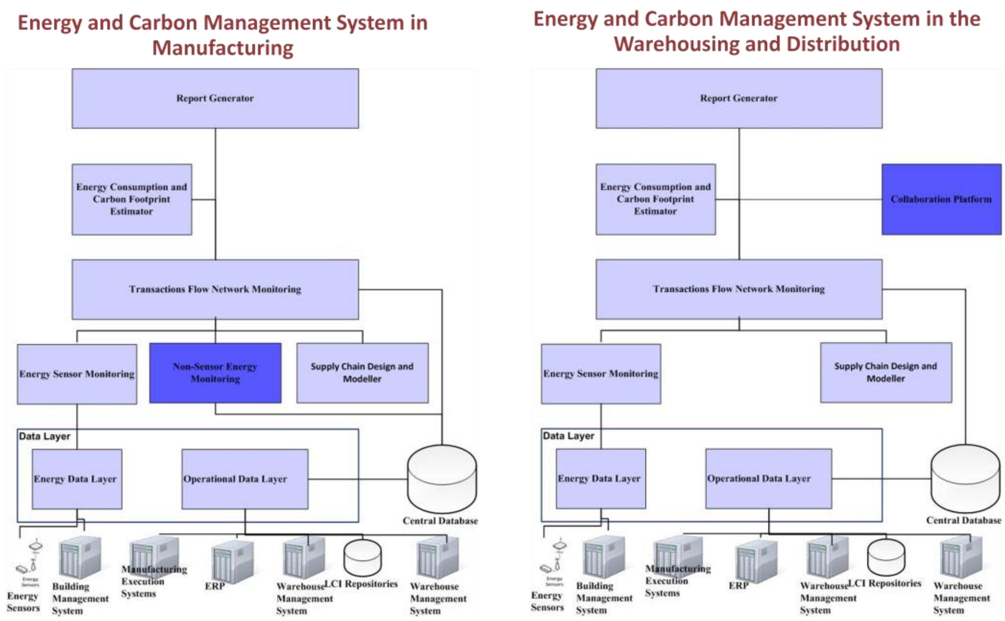


Figure 7.1: Energy and Carbon Management System Instantiations

As presented in Figure 7.1, the two instantiations share most of the generic components identified in Section 4. Therefore, we may conclude that the high-level design principles formulated by each component remain the same in all cases, hence arising sufficiently consistent across different contexts and cases. Any differentiation of these functionalities, as determined by the context settings, becomes apparent only after a more detailed consideration. Indicatively, the operational data layer manages different kind of data per case, thus yielding in a different XML schema and data interface. Similarly, the energy and carbon allocation methodologies applied in each context is different since the allocation unit in textile manufacturing cases is one square meter of the produced article while in the two cases of a supply chain the allocation unit is the volume or weight of products distributed. Calculating the indirect energy in manufacturing imposes another context-determined differentiation. As a result, the Energy and Carbon Footprint Estimator nests possibly different methodologies ensuring the reliability of the estimations, once adaptability to context specificities.

In the case of warehousing and distribution, we notice the absence of the non-sensor energy monitoring component, as there is no secondary data regarding energy consumption. However, this differentiation is mainly driven by the specific implementation in the selected cases. In another case of warehousing and distribution where secondary data regarding energy consumption are available, a non-sensor energy monitoring component could be included.

In addition, the need of handling semi-finished products and raw materials in manufacturing requires the development of a feature that maps and monitors the transformation of raw materials to semi-finished or finished products in the Transactions Flow Networking component of the manufacturing instantiation.

In the case of manufacturing, we notice the absence of the collaboration platform component as the scope of energy and carbon management is limited to an interfirm level and there is no need for interacting with other supply chain partners. However, in the warehousing and distribution case where energy and carbon management scope is extended outside a single firm's boundaries, there is a need for handling different supply chain networks and managing the relationships with external partners. Therefore, Collaboration platform components are implemented for this instantiation.

Overall, the structural similarities of the two instantiations imply that the proposed design is generic enough to cover the requirements of Energy and Carbon Management, while also admitting context-driven differentiations without altering its main principles.

Even though the suggested architectural framework and design is context- and technology independent, contextual implementation settings, such as data quality and availability, data capture and integration, may affect the design of these systems and lead to new requirements and system functionalities. Therefore, we investigate and provide empirical evidence on the main issues that emerged during the demonstration, pilot testing and evaluation of the ECMS in the various settings. We conclude with a set of challenges that are related to the following aspects presented above a) Data quality and availability, b) Data capture and integration and c) Environmental Performance Metrics selection d) Collaboration and information sharing. These aspects are further elaborated below. These findings could become a guide towards the design and the implementation of ECMS in the Manufacturing. Note that we don't claim exhaustiveness.

More specifically, the various implementation empirical findings regarding these challenges can be summarized in the following list (**eighth outcome**):

- environmental data availability
- data quality and data inconsistencies
- data granularity levels
- complexity of integrating various types of data (e.g. energy consumption data with manufacturing data or energy consumption data with and warehousing and distribution data)
- technical integration issues and absence of automation mechanisms
- dependencies and coordination problems in the workflow tracking due to the time-dependency of manufacturing data and the monitoring of semi-finished products
- dependencies and coordination problems due to the need of aligning inputs from various supply chain partners
- definition and selection of environmental and traditional performance measures
- collaboration issues and information sharing concerns

Evidently, these challenges reveal specific design and implementation principles to be implemented in order to ensure the efficacy of such systems in a real-world context (**ninth outcome**). The design principles define what a system should provide in order to cover the requirements. The implementation principles concerned with the process of setting up and maintaining the proposed class of systems. The following key findings emerged from the demonstration, pilot testing and refine the design of an ECMS.

In order to show how context driven differentiations and challenges affect the system functionalities in a lower level of analysis, we present a table with a summary of the design challenges discussed above (Section 6.5 and 6.6). We provide how these challenges affect the design and the implementation of an ECMS by presenting a set of both design (related to the Components) and implementation principles. In this way, we also discuss the aspect of artifact mutability.

Table 7.1: Implementation Challenges and the Respective Design Principles

Aspect	Design Principle	Related System Components
Environmental Data Availability	The system should manage (collect, process and store) the various types of energy and fuel consumption e.g. both actual measurements of energy sensors and energy or fuel consumption based on secondary data in order to enable a company to implement energy and carbon management based on its current data availability levels.	• Energy Data Layer • Energy Sensor Monitoring • Non-Sensor Energy Monitoring
	The system should include configuration parameters referring to data availability in the components of an ECMS that are responsible for the data uploading and storing, for conducting the energy and carbon estimations and allocations and for managing and integrating all information flows in order to adopt energy and carbon management on a firm's data availability levels.	• Energy Data Layer • Operational Data Layer • Energy Consumption and Carbon Footprint Estimator • Transactions Flow Network Monitoring
	The system should implement mechanisms for producing environmental data based on secondary transactional data e.g. a mechanism for calculating fuel consumption based on the invoices could be used as an alternative source of information.	• Non-sensor Energy Monitoring
	The system should implement general standards regarding energy sensors in order to facilitate the integration with existing energy sensors infrastructure if needed.	• Energy Sensor Monitoring • Energy Data Layer
	The system should implement an interface that will inform users about the environmental data used in the calculations ensuring data transparency.	• Report Generator
Data quality and data inconsistencies	The system should collect data that have been produced in a non-automatic way e.g. towards a user interface for uploading data that are kept in excel-like format	• Non-Sensor Energy Monitoring

Data granularity levels	The system should deploy mechanisms that will transform the data in compatible forms e.g. comparative measurement units.	• Operational Data Layer • Energy Data Layer
	The system should deploy mechanisms and business logic that produce the missing data based on the existing ones e.g. the route through shipments	• Operational Data Layer • Energy Data Layer
	The system should provide a data-cleansing mechanism that will validate and clean-up the data received in order to be integrative.	• Operational Data Layer • Energy Data Layer
	The system should provide a mechanism that will ensure that the received data are compliant to the data specification standard.	• Operational Data Layer • Energy Data Layer
	The system should inform a user regarding data quality e.g. towards a user interface in order to interpret the results in an accurate way.	• Report Generator
	The system should incorporate the data granularity as a basic configuration parameter in the components of an ECMS that are responsible for the data uploading and storing, for conducting the energy and carbon estimations and allocations and for managing and integrating all information flows.	• Energy Data Layer • Operational Data Layer • Energy Consumption and Carbon Footprint Estimator • Transactions Flow Network Monitoring
	The system should provide mechanisms that will transform data in the same granularity level e.g. mechanisms for aggregating energy consumption data on a day granularity level in order to be the same with inventories granularity levels	• Energy Data Layer • Operational Data Layer • Energy Sensor Monitoring,

Complexity of integrating various types of data (e.g. energy consumption data with and warehousing and distribution data)	The system should provide an adaptable logic of calculating and allocating environmental impacts at various levels of analysis by taking into account data granularity level, data accuracy and the availability of all data.	• Energy Consumption and Carbon Footprint Estimator
	The system should inform the user about the allocation logic or the standard implemented in order to enable him to compare and interpret the results.	• Report Generator
Technical integration issues and absence of automation mechanisms	The system should use technologies that support componentization and can improve the reusability, interoperability and integration of the systems such as, object-oriented design, web services, eXtensible Markup Language (XML), and service-oriented architecture.	• All components
	The system should provide various interfaces options in order to automate data retrieval from various systems e.g. ftp, web-services	• Energy Data Layer • Operational Data Layer
	The system should use standards for information sharing among supply chain partners in order to support Energy and Carbon Management in the Supply Chain. **(Only in Warehousing and Distribution Case)**	• Collaboration Platform
Dependencies and coordination problems due to the need of aligning inputs from various supply chain partners	The system should provide master data alignment mechanisms e.g. of products in order to support the traceability in the supply chain.	• Transactions Flow Network Monitoring • Operational Data Layer
	The system should provide mechanisms that support the coordination of all workflows e.g. orders, deliveries, and shipments of the different partners in order to enable energy and carbon management in the supply chain.	• Transactions Flow Network Monitoring

Definition and selection of energy and carbon Indicators	The system should implement a list of various assessment methodologies and energy and carbon management standards.	• Energy Consumption and Carbon Footprint Estimator
	The system should provide a list of a list of various energy and carbon indicators.	• Transactions Flow Network Monitoring
	The system should provide a user the ability to create new energy and carbon indicators if the data are available	• Transactions Flow Network Monitoring
Collaboration issues and information sharing concerns	The system should provide a feature that the definition of new partnerships and the terms of this collaboration and the management of existing ones **(Only in Warehousing and Distribution Case)**	• Collaboration Platform
	The system should provide features that will enable various types of collaboration and information exchange levels**(Only in Warehousing and Distribution Case)**	• Collaboration Platform
	The system should provide features that ensures data privacy e.g. security protocols implemented **(Only in Warehousing and Distribution Case)**	• Collaboration Platform
	The system should provide data exchange mechanisms in order to facilitate information sharing **(Only in Warehousing and Distribution Case)**	• Collaboration Platform
	The system should incorporate a calculation method that supports monitoring across	• Collaboration Platform

	supply chain that will examine and make sure that the collaborative partners have adopted compatible LCA measurement model(s), therefore the calculation of direct and indirect emissions are managed uniformly. **(Only in Warehousing and Distribution Case)**

Table 7.2: Implementation Challenges and the Respective Implementation Principles

Aspect	Implementation Principles
Environmental Data Availability	Define the type of energy and fuel consumption that should be collected and monitored and examine the environmental data availability.
	Identify the technical infrastructures that will provide them (e.g. installed energy meters) or fuel consumption meters and examine if any infrastructure investment (e.g. power meters) is needed.
	Define the process of retrieving data (e.g. what interfaces and how they should be developed, how often the data should be sent)
	Define the configuration of the ECMS related to data availability
Data quality and data inconsistencies	Define the full data dataset required for the system to support the selected Energy and Carbon Managements scope, The data requirements should also specify details regarding data granularity level by taking into account the following dimensions: time, product, physical unit (e.g. store, warehouse, vehicle, shipment, production order, machine)
	Examine whether the required data are available in the granularity level required and define the deficiencies in order to see if data deficiencies impact the provided system functionalities
	Examine if the missing or incomplete data could be produced towards a non-automatic way and used as initialization data at the system set-up phase.
	Produce a full dataset based on the available data quality and inconsistencies and validate it towards a test case scenario.
Data granularity levels	Examine the granularity levels of the required data that defined in the specification of data requirements for an ECMS
	Define the granularity levels by taking into account the available granularity levels but also other aspects such as the objective of energy and carbon management or the trade-off between the value of detail and cost of collecting,

	processing and keeping detailed information
Complexity of integrating various types of data (e.g. energy consumption data with and warehousing and distribution data)	Defining the parameters that will configure the calculation and allocation logic of the environmental impacts by taking into account the following aspects, data granularity level, data accuracy and the data availability.
Technical integration issues and absence of automation mechanisms	Define the existing systems with which the ECMS should interact in order to retrieve data in an automated way
	Investigate the existing level of automation and define the way and the technologies that the systems will interact e.g. interfaces, web services
	Investigate the existing level of information exchange and try to leverage existing information exchange relationships.
	Define the effort needed for developing automation mechanisms and decide if automation is suggested e.g. if data are required only at system set up phase an automation process may be skipped
	Conduct a repetitive process of data retrieval from existing systems for tackling integration and automation issues but also ensuring that a complete dataset with an acceptable level of data quality will be available. (**Only in Manufacturing Case**)
Dependencies and coordination problems	Define the workflows that should be tracked (e.g. shipments, products, orders) and then examine if the available workflows should be synchronized.
	Define the alignment process that should take place either as part of the set-up phase or regularly. For example, product master data alignment process across the supply chain involving supply chain partners should take place at the set-up phase of an ECMS.
	Define the processes, process steps, article with the greatest alignment in order to investigate the potential coordination problems and use them as test case scenario later on. (**Only in Manufacturing Case**)
Definition and selection of	Select the energy and carbon indicators that should be monitored and create new ones if needed in order to support

energy and carbon Indicators	decision making processes and the implementation of sustainable supply chain practices
	Select the assessment methodology and energy and carbon management standards that should be followed in order the outcomes to be comparable.
Collaboration issues and information sharing concerns	Define the terms of collaboration by making clear the mutual benefits and the effort needed for establishing the collaborative relationship (**Only in Warehousing and Distribution Case**)
	Define the various levels of collaboration in order to enable supply chain partners to engage gradually to Energy and Carbon Management practices (**Only in Warehousing and Distribution Case**)
	Define the information sharing requirements and differentiate them based on the level of collaboration (**Only in Warehousing and Distribution Case**)
	Leverage already established relationships and information sharing mechanisms (**Only in Warehousing and Distribution Case**)

The final outcome of this research (**tenth outcome**) refers to the impact of ECMS on the implementation of environmentally sustainable supply chains. We highlight how the data collected by an ECMS and the functionalities provided by it could be leveraged, in order to support energy and carbon management, environmental-aware decision-making and sustainable supply chain practices implementation. More specifically, we present initially a series of scenarios of energy and carbon management and some exemplary relevant questions that are defined based on the purpose and scope of energy and carbon management and the interaction with the users during the system demonstration and evaluation. Then, we discuss how the ECMS contributes to answering these specific questions by taking into account the KPIs and the required data and system functionalities. Aided by the energy and carbon management process and by leveraging the data and the KPIs calculated in this process, we provide some indicative types of decisions that an ECMS could support. Moreover, we show how an ECMS could support the implementation of environmentally sustainable supply chain practices by selecting an example and showing how an ECMS could provide the required data and KPIs.

Elaborating on the research outcomes, we detail and discuss the theoretical contribution and the practical implications of this research in the following paragraphs.

7.3 Theoretical Contribution

One of the main strengths of this thesis is its interdisciplinary nature, as it interweaves three different disciplines: Information Systems (IS), Operations Management and Environmental Science. Therefore, the contribution of this thesis from a theoretical perspective is found across these three disciplines and focuses on the research streams of IS Design, IS for Sustainability and Energy and Carbon Management.

The following paragraphs summarize and discuss the contribution to each of the three (3) research streams.

IS Design

The main contribution in IS design research stream can be summarized as:

1. *The formulation of an Information Systems Design Theory (ISDT) that prescribes Energy and Carbon Management Systems in the Supply Chain.*
2. *A set of design and implementation principles that correlate generic energy and carbon management implementation challenges with the design of ECMS, in order to show how these challenges affect the ECMS Design.*
3. *The definition of generic data-models describing the information flows that are required for Energy and Carbon Management.*
4. *A proof-of-concept (two artifacts) for Energy and Carbon Management Systems in the supply chain, that provide insights into how ECMS operate in practice, how they are implemented, and recommendations for their effective implementation and use.*

The business and academic research provided only a limited number of studies over the last few years that discuss the design of the broader category of EMIS. These studies mainly adopt the Design Science Approach in order to shed light on the design process of the broader category of EMIS and develop and evaluate the respective artifact (Bensch et al., 2014; Graeuler et al., 2013; Hilpert et al., 2011). They suggest architectures that include main components (such as facility management system, operating machine data middleware and architecture, sustainability assessment framework) and design principles (such as data collection automation, data collection validation), and reflect the participating systems and their interrelations as well as the corresponding data flows based on technical feasibility and business requirements. However, detailed and tangible functional and design requirements for an ECMS have not been proposed yet (Junker, 2010). Therefore, the formulation of an ISDT is suggested in order to prescribe a new class of information systems, such as ECMSs. Moreover, there is also a need of "in-field" impact of such systems in order to shed light on the implementation process and any related underlying phenomena (Malhotra et al., 2013).

As a result, this research is an effort to fill the aforementioned research needs for an ISDT for ECMS by formulating an ISDT and the respective theory components. Special emphasis has been given on the integration of the various information flows as suggested by Watson et al. (2010) and also on the implementation challenges affecting the design. Melville & Whisnant (2014) have discussed the implementation challenges of an ECMS but have not related them to the design of an ECMS. Following a design science approach, our work contributes to further specify a set of design and implementation principles that address them. More specifically, we identify the implementation challenges of these systems, we demonstrate the developed artifact in four actual cases and then specify a set of design principles that tackle these challenges.

Due to the information-intensive nature of an ECMS, its design is highly dependent on extracting information from disparate data models and "gluing" together various information flows. While there are several data models available for many aspects of the supply chain such as orders, process plans and production runs, deliveries, such data integration is of upmost importance for supporting both day-to-day operations and environmental-aware decisions. Considering that the types of data that enterprises capture are actually very similar, there are great benefits that can be derived by taking advantage of common, reusable data structures or "universal data models". As a result, this research tries also to contribute to the design of an ECMS by providing a generic data-model of the core entities per information flow, which displays the plausibility of data integration. Such data model provides semantic structures to describe data requirements for building an ECMS.

Moreover, this study provides a proof-of-concept (two artifacts) for Energy and Carbon Management Systems that provide insights into how ECMS operate in practice, how they are implemented, and recommendations for their effective implementation and use in the supply chain context.

Except from the need of conducting further research on the design of the specific class of an ECMS, Goes (2014) highlights the absence of design science research in Top Journals and subscribes to the notion that the IS field needs more design science research. Aligned with the above perception is the recent call for papers for EJIS special issue on Exemplars and criteria for applicable design science research. Therefore, this work also complements the emerging research stream that applies the Design Science approach in IS Research by

5. *Providing an exemplar of applying the Design Science research approach in the case of ECMS in the supply chain.*
6. *Using a more holistic approach that correlates the outcomes of each step of the Design Science approach with the components of the ISDT theory. More specifically, we show how the application of the 'design-science research methodology process model' suggested by Peffers et al. (2007) could support the development of the ISDT theory and inform its respective components (Gregor & Jones, 2007).*

IS for Sustainability

1. *Explore the role of IS on the development of environmental sustainable supply chains by investigating in-depth the emerging class of ECMS and position them in the broader context of information systems addressing sustainability challenges (Green IS research area).*
2. *Provide empirical evidence on how ECMS contribute to the implementation of environmentally sustainable supply chains, by supporting energy and carbon management, environmental-aware decision making and the implementation of environmentally-sustainable supply chain practices.*

The business and academic research has proliferated significantly over the last few years by studies that highlight the important role of information systems on addressing sustainability goals in general (Elliot, 2011; Jenkin et al., 2011; Melville, 2010; Watson et al., 2010) and motivate further research in the field. For example, in the MISQ special issue (Malhotra et al., 2013), three papers are published that focus on sustainability transformation themes and more specifically on the role of Green IS on organizational-, supply-side- and consumption-side transformations.

Due to the nascent nature of the Green IS area, limited research exists on discussing the role of information systems and more specifically how they could aid firms to succeed in their sustainability goals. Most of the studies are conceptual and propose general frameworks for framing research in the Green IS field. Although Green IS may take many forms and target different environmental problems, much of the extant research considers Green IS at an aggregate level (e.g., Chowdhury, 2012; Melville, 2010). In order to fully understand the variations and nuances of the relationships between information systems and environmental sustainability, it is necessary to unpack the black box of Green IS. Therefore, rather than taking a broad view of the subject, this study focuses on an emergent category of Green IS, the ECMS. Specifically, the study examines the ECMS in the context of supply chain and presents how an ECMS could support the implementation of energy and carbon management by collecting and integrating data from various sources, calculating various KPIs and providing a set of functionalities.

Moreover, we further explore the role of an ECMS on supporting the implementation of sustainable supply chains by providing empirical evidence on how they support environmental-aware decision making and the implementation of environmentally sustainable supply chain practices. More specifically, we discuss how an ECMS impacts the implementation of environmentally sustainable supply chains by highlighting how the data collected by an ECMS and the functionalities provided by them could be leveraged in order to support environmental-aware decision-making and sustainable supply chain practices implementation.

Energy and Carbon Management

1. *Frame the Energy and Carbon Management in the supply chain, by identifying a set of various dimensions related to them and the respective Key Performance Indicators (KPIs), information flows and required data.*
2. *Identify important Energy and Carbon Management implementation issues and challenges and provide empirical evidence on how to address them.*
3. *Explore the role of IS on supporting Energy and Carbon Management in the Supply Chain, by presenting how the required energy and carbon management data can be collected, integrated, processed and presented in the form of KPIs by an ECMS.*

Prior research has primarily considered the importance of energy and carbon management on addressing sustainability goals in the supply chain (Bjorklund et al., 2012; Schaltegger & Burritt, 2014;Seuring & Müller, 2008) and has identified the significant role of information systems for enabling it (Björklund et al., 2012; Dao et al., 2011; Melville, 2010). Measurement of the energy and carbon emissions is a new challenge for particularly large firms which attempt to proactively adopt sustainability management. In that end, there is a rapidly growing body of literature that focuses on the energy and carbon management and more specifically on addressing the question of how to measure it supply chain wide (Bjorklund et al., 2012; Tattichi et al., 2013). However, there is not adequate empirical evidence on which is the purpose and scope of energy and carbon management in the supply chain expressed e.g. in business needs, key performance indicators and data requirements. Whilst Burritt et al. (2011) argue for more empirical studies on energy and carbon management to bring business cases for sustainability.

In order to fill the aforementioned gap, this thesis frames the energy and carbon management by capturing the industrial requirements of energy and carbon management in the supply chain, and by suggesting different energy and carbon management dimensions. More specifically, we worked closely with different organizations in different industries to broaden understanding of Energy and Carbon Management process issues and to frame energy and carbon management. In particular, working with firms in the textile manufacturing sector and the Fast Moving Consumers Goods Sector was especially insightful, given the different business processes and sources of GHG emissions in manufacturing versus warehousing and distribution in the FMCG.

Despite the existence of a number of available tools and approaches for the practice of Energy and Carbon Management, the existing Energy and Carbon Management frameworks and tools do not explain the processes by which corporate managers collect and use carbon information within an organization (Burritt et al., 2011; Jeswani et al., 2007). Furthermore, there is a knowledge gap between the types of information required and the usefulness of this information for carbon management. That is to say that there has been little evidence obtained about what type of information should be collected, and why this information should be collected for carbon management (Lee, 2012). Therefore, we define for each one of the energy and carbon management dimensions a set of KPIs that are required to be calculated and then we identify a set of relevant information flows (contextual, transactional, environmental, product environmental) and the respective data that should be collected.

Energy and carbon management requires the integration of various information flows in order to calculate KPIs that provide an integrated view, both operational and environmental one, and expands at the whole supply chain. Therefore, energy and carbon management turns to be a demanding process in terms of both data collection and integration with existing infrastructures. By observing the implementation process and analysing the outcomes, we have been able to identify important Energy and Carbon Management implementation issues and challenges and provide empirical evidence on how to address them by suggesting a set of implementation principles.

Another research stream concerns the use of information systems on the development of Energy and Carbon Management in the Supply Chain (Banker et al., 2006; Björklund et al., 2012; Hervani et al., 2005; Melville, 2010). However, there is no adequate research that shows how an information system and more specifically an ECMS could serve Energy and Carbon Management requirements. In order to explore the role of an ECMS, we identify for each level of analysis of energy and carbon management a set of generic requirements that are consolidated in a conceptual architecture. The conceptual architecture addresses the main challenge of information flow integration consisted by various components that serve the various requirements and collects, processes and integrates the various information flows addressing in that way the main challenge of information flows integration (Watson et al, 2010).

7.4 Practical/Managerial Implications

The research outcomes may have a significant impact for practitioners in supply chain, as they capture the current needs regarding energy and carbon management, present an ECMS that addresses such needs, provide a proof-of-concept for an ECMS and provide insights regarding the impact of such systems. These outcomes offer support to software engineers/developers and vendors and organizations that are interested in implementing an ECMS in order to reap energy and carbon management benefits and more sustainable supply chains.

Firstly, the suggested ECMS design theory and the developed artifact can inform software engineers in their efforts to design an IS for energy and carbon management in the supply chain context. More specifically, the results highlight the core and intermediary principles of an ECMS design. Therefore, software engineers could use the list of design requirements and the conceptual architecture including its components as a starting point and then expand them based on further context specific requirements. Moreover, the data requirements are a critical aspect in the design of an IS and could facilitate software engineers both to the design and development of the ECMS data layer but also to the integration process with existing infrastructures.

During the demonstration of the ECMS artifact, a set of implementation issues (e.g. data and technical) have been identified and resulted in a set of principles that could constitute implementation guidelines. These guidelines could be used by practitioners in order to facilitate the ECMS implementation process.

Moreover, the suggested conceptual architecture shows a logical decomposition of the system's components that interact in order to support the desired Energy and Carbon management levels. Therefore, it supports componentization and can improve the reusability and integration of the systems providing benefits both for software engineers and software vendors. More specifically, software engineers could proceed with the development of an ECMS by exploiting components that either have been developed internally for other systems or even could be provided by an external partner. In the case of ECMSs, componentization is also required due to the expertise needed in various fields e.g. energy sensor management, energy and carbon management methodologies, supply chain management. Therefore, multiple (and not a single) companies should collaborate for the development of an ECMS. Moreover, the componentization could be the basis for developing new business models for an ECMS. For example, software vendors could provide separately the various components as software as a service.

Based on the outcomes of this thesis, supply chain managers have empirical evidence on the impact of an ECMS that could support their future decisions regarding the implementation of such a system. Moreover, they have evidence regarding the difficulties of implementing these systems, helping them to take a more informed decision. With the various levels of energy and carbon management identified, the supply chain managers can approach the implementation of an ECMS in a gradual process by implementing the energy and carbon management dimensions that are more aligned with company maturity, measurable data and available information systems and tools and the expected benefits.

7.5 Limitations & Future Research

So far, we have discussed the main contribution of this doctoral research. Now, we underline the issues that can be considered as limitations. Naturally, there is always a positive view of limitations because they recognize that there is ample ground for further research.

One important limitation lies in the limited empirical basis, which involves the risk of focusing on specific conditions rather than on general concepts. We try to minimize this risk by basing our results on previous studies and validating the outcomes with many other industrial experts apart from those directly involved in the actual system implementation. Although our study curtails this limitation by validating the outcomes of system implementation within four different cases and other industrial experts, the occurrence of further empirical evidence could shed further light on the design propositions. Future research may cover different industries and cases in order to further validate the ISDT theory.

The aim of this research is not to present an exhaustive set of Design Requirements for an ECMS, but rather to frame firstly Energy and Carbon Management and then outline some essential requirements for these systems and demonstrate the applicability of design theory. However, the lack of exhaustiveness could be considered as one more limitation. Further research could capture case specificities such as technological maturity, environmental strategy or motives behind the use of such systems and investigate how they could affect an ECMS design. Moreover, another research stream may focus on the important aspect of data granularity levels (Watson et al., 2010) and investigate the relationship between granularity levels and their impact on energy and carbon management.

As noted by Gregor & Hevner (2013), some degree of flexibility may be allowed in judging the degree of evaluation needed when new DSR contributions are made. Particularly with very novel artifacts, a “proof-of-concept” may be sufficient. In our case, we give significant effort on designing and developing an artifact, also formulate the design theory and conduct the final evaluation and impact assessment in the limited context of four cases and specific business scenarios. Therefore, a more extensive impact assessment of an ECMS could be another fruitful topic for future research. For example, we could assess the impact of an ECMS in both financial and environmental terms.

In our study, we explore the role of an ECMS in decision making and the implementation of sustainable supply chain practices by providing some first empirical evidence. However, further research is required in order to show how an ECMS could support various decision-making scenarios and various supply chain practices. In a future research, we could expand our research by exploring the role of an ECMS in the development of sustainable supply chains. In that way, we will be able to get a more in depth understanding of the role of these systems. Moreover, the role of an ECMS could be further explored by using the prominent IS theory of functional affordances (Seidel et al., 2013). By using functional affordances as theoretical lenses, we could identify the functional affordances that emerged by ECMS and that could contribute to more sustainable supply chain processes.

Last but not least, another stream of research could focus on the adoption of an ECMS and the implementation processes. For example, questions such as which motives or pressures apply to firms regarding energy and carbon management, how they are perceived and how they affect the implementation of an ECMS, which is the strategy behind the implementation of an ECMS are yet unanswered. For example, one possible direction as came by our exploratory research could include examining in more depth the different dimensions of IT-strategic alignment from an environmental perspective. The various IT applications and information systems that materialize an environmental IS strategy could be further explored. Moreover, the impact of an environmental IS strategy on both environmental and other corporate performance indicators could be further explored. Related to this, it would be especially valuable to understand the relationship between adoption of these systems and the impact on a firm's performance including not only environmental but also traditional firm's performance indicators.

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Appendix A: Industry Survey on Energy and Carbon Management and Environmental Practices

Environmental Practices

1. ***Has your firm deployed or is considering to deploy any of the following environmental practices?***
(1 = We know little about this practice
2 = We know about this practice, but do not do it
3 = We know much about this practice, but do not do it
4 = We have considered the deployment of this practice but haven't decided whether to do it or not
5 = We do this from time to time
6 = We do this most of the time
7 = We do this all of the time
8 = N/A)

Process Design Environmental Practices								
Process design focused on reducing energy and natural resources consumption in operations	1	2	3	4	5	6	7	8
Use of renewable energy (solar, wind, hydro, etc.)	1	2	3	4	5	6	7	8
Environmental criteria in supplier selection	1	2	3	4	5	6	7	8
Shipments consolidation	1	2	3	4	5	6	7	8
Selection of cleaner transportation means	1	2	3	4	5	6	7	8
Recyclable or reusable packaging/containers in logistics	1	2	3	4	5	6	7	8
Energy consumption monitoring systems	1	2	3	4	5	6	7	8
Product Design Environmental Practices								
Substitution/Reduction of polluting and hazardous materials/parts	1	2	3	4	5	6	7	8
Product design focused on reducing energy consumption and waste generation	1	2	3	4	5	6	7	8
Product design for disassembly, reusability and recyclability	1	2	3	4	5	6	7	8
Application of Life Cycle Assessment to measure products' carbon footprint	1	2	3	4	5	6	7	8
Organizational and Communication Environmental Practices								
Clear objectives and long-term environmental plans	1	2	3	4	5	6	7	8
Full-time employees devoted to environmental management	1	2	3	4	5	6	7	8
Natural environment training programs for managers and employees	1	2	3	4	5	6	7	8
Constructing low-carbon facilities	1	2	3	4	5	6	7	8
Systems for reporting and measuring the performance of the environmental business practices	1	2	3	4	5	6	7	8
Environmental arguments in marketing	1	2	3	4	5	6	7	8
Online collaboration tools (beyond email) to substitute travel or employee telecommuting	1	2	3	4	5	6	7	8
Communication to end consumers of product environmental characteristics	1	2	3	4	5	6	7	8
Use of environmental management system (e.g. ISO 14000)	1	2	3	4	5	6	7	8
Conducting in-store promotions focusing on environmental issues	1	2	3	4	5	6	7	8

Energy and Carbon Management and Collaboration

2. ***To what extent has your firm been engaged in the following activities with your primary suppliers (if you are a retailer) or major customers (otherwise) during the past two years?***
(1=Not at all, 4=Moderately, 7=Great extent)

Achieving environmental goals collectively	1	2	3	4	5	6	7
Developing a mutual understanding of responsibilities regarding environmental performance	1	2	3	4	5	6	7
Working together to reduce environmental impact of our activities	1	2	3	4	5	6	7
Making joint decisions about ways to reduce overall environmental impact of our product	1	2	3	4	5	6	7
Our firm collaborates to enhance marketing communication on environmental issues	1	2	3	4	5	6	7

3. ***When did your company employ or plan to employ the following practices for monitoring environmental impacts (energy consumption and carbon emissions)?***
(1 =3 years ago or more
2 = about 2 years ago
3 = about 1 year ago
4 = it is currently under consideration
5 = in about 1 year
6 = in about 2 years
7 = in 3 years or later)

Methods for monitoring carbon emissions	1	2	3	4	5	6	7
Software package for monitoring carbon emissions	1	2	3	4	5	6	7
Methods for monitoring energy consumption	1	2	3	4	5	6	7
Software package for monitoring energy consumption	1	2	3	4	5	6	7
Collaborating programs with its primary supply chain partners (major customers or primary suppliers) to monitor the environmental performance of products	1	2	3	4	5	6	7
Sharing information electronically with its primary supply chain partners in order to monitor energy consumption	1	2	3	4	5	6	7
Sharing information electronically with its primary supply chain partners in order to monitor carbon emissions	1	2	3	4	5	6	7

4. ***Which of the following two metrics does your firm mainly monitor or is more interested in monitoring it?***

Carbon emissions	
Energy consumption	
None	

5. ***If you think that both metrics are equally important for your firm in terms of monitoring, please check here***

☐

6. ***Why does your firm monitor the above selected metric or is more interested in monitoring it? (Please allocate 100 points to indicate the importance of each reason)?***

Cost reduction	
Enhancing the firm's environmental profile	
Increase its market share	

7. To what extent have the following performance indicators been affected by implementing environmental practices in your firm? (1=Not at all, 4=Moderately, 7=Great extent)

Reduction of carbon emissions	1	2	3	4	5	6	7
Reduction of energy consumption	1	2	3	4	5	6	7
Corporate image improvement	1	2	3	4	5	6	7
Profit decrease	1	2	3	4	5	6	7
Profit increase	1	2	3	4	5	6	7
Operational cost reduction	1	2	3	4	5	6	7
Operational cost increase	1	2	3	4	5	6	7
Increase of investment	1	2	3	4	5	6	7
Sales increase	1	2	3	4	5	6	7
Training cost increase	1	2	3	4	5	6	7

8. To what extent do you agree / disagree with the following statements? (1=Strongly Disagree, 4=Neither Agree nor Disagree, 7=Strongly Agree)

Customers who are aware of our firm's engagement in environmentally responsible actions evaluate our company very positively	1	2	3	4	5	6	7
Prospective customers, who are not aware of our firm's engagement in environmentally responsible actions, would evaluate our company very positively	1	2	3	4	5	6	7

IF YOU HAVE SELECTED CARBON EMISSIONS ABOVE, PLEASE ANSWER THE FOLLOWING THREE QUESTIONS:

9. To what extent do you agree / disagree with the following statements regarding the monitoring of carbon emissions? (1=Strongly Disagree, 4=Neither Agree nor Disagree, 7=Strongly Agree)

Monitoring carbon emissions can be implemented progressively. An initial stage of development can bring benefits to our firm and the environment even if the next stages will not be implemented	1	2	3	4	5	6	7
Monitoring of carbon emissions is a necessary prerequisite for our firm in order to develop relevant environmental actions in the future	1	2	3	4	5	6	7
The resources (capital, labor, technological infrastructure, software) needed for monitoring carbon emissions can be reused for another/ different purpose in our firm	1	2	3	4	5	6	7
Monitoring carbon emissions can be easily expanded in our firm (e.g. to another facility, in another part of the supply chain, in another product)	1	2	3	4	5	6	7
The risk regarding the investment on monitoring carbon emissions can be resolved if the investment is postponed and implemented in the future	1	2	3	4	5	6	7

10. To what extent does your firm monitor carbon emissions by implementing one of the following methods? (1=Not at all, 4=Moderately, 7=Great extent)

Measuring carbon emissions during a product's production	1	2	3	4	5	6	7
Calculating the transportation emissions of employees to and from work	1	2	3	4	5	6	7
Measuring carbon emissions in warehouse operations, including equipment, heating, refrigeration and other activities	1	2	3	4	5	6	7
Measuring road transportation emissions (e.g. fuel) related to the movement of goods in between factories or distribution centers and the final destination (shops or retailers' DC)	1	2	3	4	5	6	7
Exchanging information with logistics partners about the emissions of their fleet	1	2	3	4	5	6	7
Receiving information about the carbon emissions of raw materials or products from suppliers	1	2	3	4	5	6	7
Providing information about the carbon emissions of produced products to supply chain partners	1	2	3	4	5	6	7
Measuring carbon emissions at the point of sales	1	2	3	4	5	6	7
Measuring carbon emissions during the use of a product	1	2	3	4	5	6	7
Measuring carbon emissions at the end of a product's life cycle	1	2	3	4	5	6	7

Using environmentally extended input-output (EEIO) models	1 2 3 4 5 6 7
Executing life cycle assessment studies on own products	1 2 3 4 5 6 7

11. ***To what extent does your firm measure and report the following indices related to carbon emissions?*** *(Please select a number from 1 to 7 based on the following:*
1 = Not measured
2 = Occasionally estimated
3 = Regularly estimated
4 = Both estimate and actual data used
5 = Occasionally measured based on actual data
6 =Regularly measured based on actual data
7 =Automated reports generated based on actual data)

Vehicle fill rate	1 2 3 4 5 6 7
Vehicle capacity	1 2 3 4 5 6 7
Vehicle fuel consumption	1 2 3 4 5 6 7
Vehicle travel distances	1 2 3 4 5 6 7
On-time deliveries	1 2 3 4 5 6 7
Electricity consumption for each facility (warehouse, stores etc.)	1 2 3 4 5 6 7
Warehouse utilization	1 2 3 4 5 6 7
Inventory (measured in days)	1 2 3 4 5 6 7
Number of orders processed in a warehouse per day	1 2 3 4 5 6 7
Number of times a product is handled	1 2 3 4 5 6 7
Time a product is stored in a location	1 2 3 4 5 6 7
Vehicle occupancy in conjunction with the height of the pallets and the total used area of the truck (height-correct loading)	1 2 3 4 5 6 7
Volume of pallets, where each pallet has different products so as to create full loads (estimation of pallets volume according to the customer order)	1 2 3 4 5 6 7
Volume of damaged products	1 2 3 4 5 6 7

IF YOU HAVE SELECTED ENERGY CONSUMPTION ABOVE, PLEASE ANSWER THE FOLLOWING THREE QUESTIONS:

12. To what extent do you agree / disagree with the following statements regarding the monitoring of energy consumption? (1=Strongly Disagree, 4=Neither Agree nor Disagree, 7=Strongly Agree)

Monitoring energy consumption can be implemented progressively. An initial stage of development can bring benefits to our firm and the environment even if the next stages will not be implemented	1 2 3 4 5 6 7
Monitoring energy consumption is a necessary prerequisite for our firm in order to develop relevant environmental actions in the future	1 2 3 4 5 6 7
The resources (capital, labor, technological infrastructure, software) needed for monitoring energy consumption can be reused for another / different purpose in our firm	1 2 3 4 5 6 7
Monitoring energy consumption can be easily expanded in our firm (e.g. to another facility, in another part of the supply chain, in another product)	1 2 3 4 5 6 7
The risk regarding the investment on monitoring energy consumption can be resolved if the investment is postponed and implemented in the future	1 2 3 4 5 6 7

13. To what extent does your firm monitor energy consumption by implementing one of the following methods? (1=Not at all, 4=Moderately, 7=Great extent)

Measuring the energy consumed during a product's production	1 2 3 4 5 6 7
Measuring the energy use in warehouse operations, including equipment, heating, refrigeration and other activities	1 2 3 4 5 6 7
Measuring the energy consumption related to the movement of goods in between factories or distribution centers and the final destination (shops or retailers' DC)	1 2 3 4 5 6 7
Receiving information about the energy consumption of raw materials/ products from suppliers	1 2 3 4 5 6 7

Providing information about the energy consumption of produced products to supply chain partners	1	2	3	4	5	6	7
Measuring energy consumption at the point of sales	1	2	3	4	5	6	7
Measuring energy consumption during the use of a product	1	2	3	4	5	6	7
Measuring energy consumption at the end of a product's life cycle	1	2	3	4	5	6	7
Using environmentally extended input-output (EEIO) models	1	2	3	4	5	6	7
Executing life cycle assessment studies on own products	1	2	3	4	5	6	7

***14. To what extent does your firm measure and report the following indices related to energy consumption (Please select a number from 1 to 7 based on the following*:**

1=Not measured
2=Occasionally estimated
3=Regularly estimated
4=Both estimate and actual data used
5= Occasionally measured based on actual data
6=Regularly measured based on actual data
7 =Automated reports generated based on actual data)

Vehicle fuel consumption	1	2	3	4	5	6	7
Vehicle travel distances	1	2	3	4	5	6	7
On-time deliveries	1	2	3	4	5	6	7
Electricity consumption for each facility (warehouse, stores etc.)	1	2	3	4	5	6	7
Warehouse utilization	1	2	3	4	5	6	7
Inventory (measured in days)	1	2	3	4	5	6	7
Number of orders processed in a warehouse per day	1	2	3	4	5	6	7
Number of times a product is handled	1	2	3	4	5	6	7
Time a product is stored in a location	1	2	3	4	5	6	7
Vehicle occupancy in conjunction with the height of the pallets and the total used area of the truck (height-correct loading)	1	2	3	4	5	6	7
Volume of pallets, where each pallet has different products so as to create full loads (estimation of pallets volume according to the customer order)	1	2	3	4	5	6	7
Volume of damaged products	1	2	3	4	5	6	7

Organization's environmental and communication strategy

15. To what extent do you agree / disagree with the following statements regarding the environmental strategy of your organization? (1=Strongly Disagree, 4=Neither Agree nor Disagree, 7=Strongly Agree)

Our firm has a clear policy statement urging environmental awareness in every area of operations	1	2	3	4	5	6	7
Environmental preservation is a high priority activity in our firm	1	2	3	4	5	6	7
In our firm, environmental preservation is largely an issue of maintaining a good public image	1	2	3	4	5	6	7
Environmental preservation is vital to our firm's survival	1	2	3	4	5	6	7
At our firm, we make every effort to link environmental objectives with other corporate goals	1	2	3	4	5	6	7
Our firm is engaged in developing products and processes that minimize environmental impact	1	2	3	4	5	6	7
We emphasize the environmental aspects of our products and services in our advertisements	1	2	3	4	5	6	7
The marketing strategies of our products and services have been considerably influenced by environmental concerns	1	2	3	4	5	6	7

16. To what extent do you communicate with your primary suppliers (if you are a retailer) or major customers (in any other case)? (1=never, 4=sometimes, 7=always)

Our firm provides information to help our primary partners (primary suppliers or major customers respectively) to improve	1	2	3	4	5	6	7
Our firm exchanges operational and logistical information with primary partners	1	2	3	4	5	6	7

Our firm informs our primary partners about events or changes that may affect them	1	2	3	4	5	6	7
Our firm has face-to-face communication with primary partners for planning purposes	1	2	3	4	5	6	7

17. To what extent do you agree / disagree with the following statements regarding your supply chain information infrastructure? (1=Strongly Disagree, 4=Neither Agree nor Disagree, 7=Strongly Agree)

Automatic data capture systems are used (e.g., barcode) across our firm's supply chain	1	2	3	4	5	6	7
Our firm has implemented technologies enabling automatic and unique product identification (e.g. RFID)	1	2	3	4	5	6	7
Definitions of key data elements (e.g., customer, order, part number) are common across our firm's supply chain	1	2	3	4	5	6	7
Supply chain transaction applications (e.g.. order management, procurement, manufacturing and distribution) communicate in real time	1	2	3	4	5	6	7
Supply chain applications with internal applications of our organization (such as enterprise resource planning) communicate in real time	1	2	3	4	5	6	7
Supply chain-wide inventory is jointly managed with suppliers and logistics partners	1	2	3	4	5	6	7
Performance metrics are shared across our firm's supply chain	1	2	3	4	5	6	7
We share actual sales data with our major supply chain partners (e.g., distributors, wholesalers, retailers)	1	2	3	4	5	6	7

18. To what extent do you agree / disagree with the following statements regarding the level of environmental information your firm holds compared to your primary suppliers (if you are a retailer) or major customers (in any other case)? (1=Strongly Disagree, 4=Neither Agree nor Disagree, 7=Strongly Agree)

Our firm can quantitatively assess the environmental impact of its products more accurately than its primary supply chain partners	1	2	3	4	5	6	7
Our firm holds more information about the environmental impact of its products than its primary supply chain partners	1	2	3	4	5	6	7
Our firm cannot easily communicate its environmental performance to its primary supply chain partners	1	2	3	4	5	6	7
Our company is not able to adequately assess the environmental impact of its primary partners' processes	1	2	3	4	5	6	7

Reasons for Implementing Environmental Business Practices

19. To what extent do you agree / disagree with the following statements regarding the reasons for adopting environmental business practices? (1=Strongly Disagree, 4=Neither Agree nor Disagree, 7=Strongly Agree)

The top management team in our firm is committed to environmental preservation	1	2	3	4	5	6	7
Our firm's environmental efforts receive full support from our top management	1	2	3	4	5	6	7
The public is very concerned about environmental destruction	1	2	3	4	5	6	7
Our customers are increasingly demanding environmentally friendly products and services	1	2	3	4	5	6	7
Regulation by government agencies has greatly influenced our firm's environmental strategy	1	2	3	4	5	6	7
Our industry is faced with strict environmental regulation	1	2	3	4	5	6	7
Being environmentally conscious can lead to substantial cost advantages for our firm	1	2	3	4	5	6	7
Our firm can increase market share by making our current products more environmentally friendly	1	2	3	4	5	6	7
Cost savings is the main reason for implementing environmental practices	1	2	3	4	5	6	7
Through collaboration with the supply chain partners, our firm can enhance its marketing communication on environmental issues	1	2	3	4	5	6	7

20. How important do you consider each of the following influences on the implementation of environmental practices? (1=not important, 4=moderately important, 7=very important)

Domestic customers	1	2	3	4	5	6	7
International customers	1	2	3	4	5	6	7
Domestic suppliers	1	2	3	4	5	6	7
International suppliers	1	2	3	4	5	6	7
Employees	1	2	3	4	5	6	7
Shareholders	1	2	3	4	5	6	7
Financial institutions	1	2	3	4	5	6	7
Domestic competitors	1	2	3	4	5	6	7
International competitors	1	2	3	4	5	6	7
International agreements	1	2	3	4	5	6	7
ENGOs	1	2	3	4	5	6	7
Media	1	2	3	4	5	6	7
National governments	1	2	3	4	5	6	7
Local public agencies	1	2	3	4	5	6	7

Demographics

Which department do you work in?

☐ *Directors*
☐ *Supply Chain*
☐ *Marketing*
☐ *Sales and Customer Support*
☐ *Buying*
☐ *Human Resources*
☐ *IT*
☐ *Accounting*
☐ *Environmental Management*
☐ *Other (please indicate):*

Which is your current position in the organization?

☐ *CEO/Owner/Director*
☐ *Senior Management*
☐ *Middle Management*
☐ *Employee*
☐ *External Partner*
☐ *Other (please indicate):*

What of the following do you represent?

☐ *Headquarters of a multinational company*
☐ *Local organization of a multinational company*
☐ *Local firm*

What is the type of your firm?

☐ *Retailer*
☐ *Manufacturer*
☐ *Supplier*
☐ *Third Party Logistics (3PL) company*
☐ *Other (please indicate):*

How many employees work in your company?

☐ *Less than 50*
☐ *50 - 99*
☐ *100 - 499*
☐ *500 - 999*
☐ *1,000 - 4,999*
☐ *5,000 or more*

Which is the industry / sector your organization belongs to?

☐ *Food*
☐ *Soaps and detergent*
☐ *Retail*
☐ *Textiles and Clothing*
☐ *Information and Communication Technologies*
☐ *Energy*
☐ *Footwear*
☐ *Automotive*
☐ *Furniture*
☐ *Leather*
☐ *Transportation*
☐ *Other (please indicate):*

For retail organizations only:

What is your company's number of stores? _______________

What is your company's market position in terms of market share*?:*

1=among top 3
2=among top 5
3=among top 10
4=among top 20
5= among top 30
6=middle range
7=lower end

For supplier/ manufacturers only:

Number of product lines: _______________
Number of product categories: _______________

How would you rate your company's products overall in terms of market share?:

1=they are leaders (#1 or #2) in all the respective categories
2=they are leaders (#1 or #2) in most of the respective categories
3=they are leaders (#1 or #2) in few of the respective categories
4=they are #3 or #4 most of the times

What is your firm's annual turnover (in million euros)? ☐ *<2* ☐ *2-10* ☐ *10-50* ☐ *50-150* ☐ *150-250* ☐ *>250*	*5=they are #3 or #4 sometimes* *6=they are in a middle to lower position in their categories* *7=they are rather in the lower positions in their categories* ***What is your firm's annual turnover (in million euros)?*** ☐ *<2* ☐ *2-5* ☐ *5-10* ☐ *10-50* ☐ *50-100* ☐ *>100*
For Third Party Logistics (3PL) companies only: ***Number of vehicles: ___________*** ***Number of nodes:___________*** ***Distribution area:___________*** ***Number of customers:__________***	***What is your firm's annual turnover (in million euros)?*** ☐ *<2* ☐ *2-5* ☐ *5-10* ☐ *10-50* ☐ *50-100* ☐ *>100*
What is the country of operations for your firm? ______________	

Appendix B: Industry Survey Data Collection, Analysis and Results

To test our research hypotheses, a survey approach was followed, using the firm as unit of analysis. A detailed questionnaire has been used as research instrument. The survey ran for three months and was addressed to firms in the fast-moving consumer goods (FMCG) industry. We chose to focus on this industry due to their extensive interest in addressing various environmental issues. Target respondents were senior managers or middle managers with direct responsibility for environmental issues. In case there was no person in the organization devoted to environmental management, target respondents were senior managers or middle managers with direct responsibility for supply chain management or logistics.

The survey was conducted at European level and was supported by the Efficient Consumer Response (ECR) Europe organization. ECR Europe is a joint trade and industry body, launched in 1994 to make the FMCG sector as a whole more responsive to consumer demand and promote the removal of unnecessary costs from the supply chain. To collect the required data, an email invitation was sent by ECR Europe to all its member organizations across Europe, inviting target respondents to participate in the survey. To encourage participation, it was communicated that the results of the survey would be provided to each participant at the end of the survey. Each company was asked to respond only once to the online questionnaire. The survey ran from March 2012 to June 2012. The response rate varied in the different European countries and ranged from 12% to 50%. A total of 75 valid questionnaires have been collected.

To analyze the questionnaire data, examine the research model and test the hypotheses, a variety of analytic techniques and tools was used. SPSS software was used to organize the data and run preliminary descriptive analyses. The examination of the research model and the hypotheses testing was performed using the Structural Equation Modelling (SEM) technique using Partial Least Squares (PLS). PLS was chosen as it is more appropriate than LISREL-type models when sample sizes are small, models are complex and the goal of the research is in explaining variance (Smith & Barclay, 1997). PLS estimation makes no distributional assumptions about the sample data. Therefore, for concluding on the significance of parameters, estimated bootstrap estimates of standard errors were utilized (White et al., 2003).

Measures

The measures employed in the present study have been adapted from the extant literature. Environmental Corporate Strategy and Environmental Marketing Strategy were measured with two items and the responses were given on a seven-point Likert-type scale with the endpoints Strongly Disagree (1) and Strongly Agree (7). Environmental Performance was measured as improvements perceived by managers in relation to carbon emissions and energy consumption and the responses were given on a seven-point Likert-type scale with the endpoints Not at all (1) and Great extent (7).

For measuring the realized Environmental IS Strategy the implementation and use of environmental monitoring systems was examined, as already discussed. More specifically, two items referred to the use of environmental monitoring information systems were used and the responses were given on a seven-point Likert-type scale with the endpoints being "We know little about this" (1) and "We use this all the time" (7).

The small number of indicators used for each construct could be a limitation of our study. However, the satisfactory levels of measurement validity and internal consistency, that results have shown, alleviate this limitation. Moreover, the scenario and survey procedure we have followed calls for parsimonious measurement scales in order to avoid respondents' fatigue.

The following table presents the constructs and the respective items used for measurement.

Table B.1: Research model constructs and respective items

Construct	Measurement Item	Source
Environmental Corporate Strategy	• At our firm, we make every effort to link environmental objectives with other corporate goals • Our firm is engaged in developing products and processes that minimise environmental impact	Banerjee et al., 2003
Environmental Marketing Strategy	• We emphasise the environmental aspects of our products and services in our advertisements • The marketing strategies of our products and services have been considerably influenced by environmental concerns	Banerjee et al., 2003
Environmental Performance	• Reduction of carbon emissions • Reduction of energy consumption	Zhu et al., 2005
Environmental IS Strategy	• Energy consumption monitoring systems • Systems for reporting and measuring the performance of the environmental business practices	

Data Analysis

A structural equation modelling approach was used to measure the relationships proposed by our research model. This method was applied as it tests structural and measurement models and provides a complete analysis for interrelationships in a model. A variance-based partial least squares (PLS) method was chosen over covariance-based methods, such as LISREL, as it supports both exploratory and confirmatory research. The SmartPLS software was used (Ringle et al., 2005). PLS does not generate an overall goodness-of-fit index (as LISREL), so model validity is assessed by examining structural paths and R2 values. Bootstrapping was performed to test statistical significance of each path coefficient using t-tests. We estimated the significance of the parameters on the basis of 1000 bootstrapped samples (White et al., 2003).

Prior to any model examination or hypothesis testing we should ensure the validity of the measurement model. We tested our measurements for internal consistency, convergent and discriminant validity, employing the testing system recommended by Fornell & Larcker (1981). Internal consistency of our constructs is acceptable, as all the reliabilities – as measured by Cronbach's a indicator – exceed the 0.70 guideline that Nunnally (1978) recommends.

Convergent validity assures that all the measures measure a specific construct and the convergent validity of each construct is shown when all the measures of a certain construct correlate. Convergent validity can be assessed by a) reliabilities of items in each scale, b) the composite reliability of each construct and c) Average Variance Extracted (AVE). Reliability of items is assessed by examining each item's loading on its construct. As shown in Table 5 (see Appendix), all the items exceed the 0.60 recommended threshold for exploratory research (Nunnally, 1978) and most of them exceed 0.90. Composite reliability assesses the internal consistency of a measure and is a measure of the overall reliability of a collection of heterogeneous but similar items. The composite reliability of every construct should exceed the 0.70 threshold (Hair et al., 1998). Average Variance Extracted assesses the magnitudes of variance that a variable captures from its indicators compared to the amount that results from measurement error. The AVE of each construct is recommended to exceed the 0.50 threshold (Fornell & Larcker, 1981). As shown in Table 4, all constructs have exceeded the thresholds of both composite reliability and AVE.

Table B.2: Reliability, correlation matrix, and average variance extract

	Cronbach's Alpha	*Composite Reliability*	*AVE*	*1*[2]	*2*	*3*	*4*
Environmental Corporate Strategy	0.82	0.84	0.92	**0.96**	0	0	0
Environmental Marketing Strategy	0.90	0.91	0.95	0.57	**0.95**	0	0
Environmental Performance	0.75	0.80	0.89	0.40	0.30	**0.89**	0
Environmental IS Strategy	0.88	0.89	0.94	0.33	0.25	0.59	**0.94**

Note: The diagonal elements represent the square root of AVE and the off-diagonal the correlations.

Discriminant validity is concerned with the discrimination among measures of different constructs. Discriminant validity is shown when the PLS indicators (a) load much higher on their hypothesized factor than on other factors (own-loadings are higher than cross-loadings), and (b) when the square root of each factor's Average Variance Extracted (AVE) is larger than its correlations with other factors (Gefen & Straub, 2005). As shown in the following Table, the results support that there is discriminant validity, according to the test of Fornell & Larcker (1981).

Table B.3: Constructs, items, and loadings

Environmental Corporate Strategy	At our firm, we make every effort to link environmental objectives with other corporate goal	0.91
Environmental Corporate Strategy	Our firm is engaged in developing products and processes that minimise environmental impact	0.93
Environmental Marketing Strategy	We emphasise the environmental aspects of our products and services in our advertisements	0.94
Environmental Marketing Strategy	The marketing strategies of our products and services have	0.97

[2] 1 = Environmental Corporate Strategy, 2 = Environmental Marketing Strategy, 3 = Environmental performance, 4 = Environmental IS Strategy

	been considerably influenced by environmental concerns	
Environmental IS Strategy	Use energy consumption monitoring systems	0.94
Environmental IS Strategy	Use systems for reporting and measuring the performance of the environmental business practices	0.95
Environmental Performance	Reduction of carbon emissions	0.91
Environmental Performance	Reduction of energy consumption	0.88

Appendix C: ECMS Design Requirements and Conceptual Architecture

This section presents the relation of the components and the aforementioned design requirements presented in Chapter 4.

Table C. 1: Energy and Carbon Management Systems Design Requirements and the respective ECMS Components

Requirements	Explanation	Component
Energy and fuel consumption data collection	Energy consumption from energy meters needs to be collected, the energy streams needs to be handled and alerting mechanisms needs to be supported where applicable for enhancing energy and carbon efficiency.	Energy Data Layer, Energy Sensor Monitoring
Operational data collection	Information about transactions (production processes, distribution process) and contextual information e.g. regarding the machines, processes, products, inventories deliveries, partnerships needs to be collected.	Operational Data Layer
Energy consumption data collection from non-sensor resources	The management and utilization of energy consumption flows non-recorded by sensors needs to be supported. Such flows include for example the information coming from energy audits, as translated into energy vectors or energy consumption bills or fuel refills.	Non-sensor Energy Monitoring
Environmental impacts estimation	A business logic that will enable the calculation of carbon emissions and the allocation of environmental impacts on more detailed level of analysis, e.g. process, product etc. needs to be implemented.	Energy Consumption and Carbon Footprint Estimator
Workflow monitoring	The monitoring and the supervision of the various supply chain processes needs to be supported.	Transactions Flow Network Monitoring
Environmental reporting	The required Key Performance Indicators needs to be presented in various formats.	Report Generator

Supply chain modelling	The design and modelling of the various supply chain processes and networks needs to be supported	Supply Chain Design and Modeler
Information exchange	Information sharing, information synchronisation and the collaboration with supply chain partners needs to be supported.	Collaboration Platform
Integration Support	Various interfaces needs to be provided for ensuring the integration with the existing systems	Collaboration Platform
Intraorganizational collaboration and coordination	The coordination of the processes and the data received from the various supply chain partners needs to be supported.	Operational Data Layer, Collaboration Platform

Table C.2: Energy and Carbon Management System Requirements related to KPIs and the respective ECMS components

Requirements	**Explanation**	**Component**
Estimating KPIs	A business logic that will enable the calculation of the required Key Performance Indicators needs to be implemented	Energy Consumption and Carbon Footprint Estimator
Configuring KPIs Calculation Logic	The ability to configure the KPIs calculation logic parameters needs to be provided.	Energy Consumption and Carbon Footprint Estimator
Defining New KPIs	The definition of new Key Performance Indicators needs to be supported.	Supply Chain Design and Modeler

Table C.3: Energy and Carbon Management Systems Design Requirements related to data and the respective components

Requirements	Explanation	Component
Data validation	Validate and cleansing-up the data received is needed in order to the date to be integrative.	Operational Data Layer
Data specification compliance	The received data is needed to be compliant to the data specification standard for the ECMS.	Operational Data Layer
Automated input interfaces	Automated input interfaces are required in order to enable the collection of environmental and operational data from existent business information systems automatically.	Operational Data Layer
Provision of quality indices regarding data availability	The data availability needs to be examined and the respective indices related to it needs to be provided.	Operational Data Layer
Ensuring the same level of	The data received is needed to have the same level of granularity e.g.	Operational Data Layer

granularity	inventories from all warehouses and stores should be stored on a daily basis.	
Data transparency	Information about data type and origin as well as collection proofs regarding the environmental and operational data e.g. secondary environmental data are used for the estimations should be provided	Operational Data Layer
Data synchronization and mapping	Mapping the entities and synchronizing the data received from other resources e.g. map the codes for products from different suppliers is needed.	Operational Data Layer

Appendix D: Energy and Carbon Management Data Requirements

In order to support the energy and carbon management level and the calculation of the various KPIs, we have identified the data entities and the respective data flows that are required. The data entities were classified in the following categories of information flows: Transactional information flow (TI), Contextual information flow (CI), Environmental information flow (EC), Product environmental information flow (PEIF). Figure 1 and 2depicts data entities along with their respective flows in a unified data model respectively for the cases of manufacturing and warehousing and distribution We have colored each entity according to the flow it belongs to with different colors: Transactional information flow (TI) entities are colored with light blue, Contextual information flow (CI) entities are colored with red, Environmental information flow (EC) entities are colored with light green, Product environmental information flow (PEIF) entities are colored with grey. Additionally, a description of these entities appears in Table 1 and Table 2 respectively. Moreover, Table 1 and 2 presents the source of these data as well as the granularity level of this information, by taking into account the following dimensions: time, product, physical unit (e.g. store, warehouse, vehicle, shipment, production order, machine).The data model and the table present the minimum required list of data entities that are required in order to support the various dimensions that have been defined in manufacturing and warehousing and distribution.

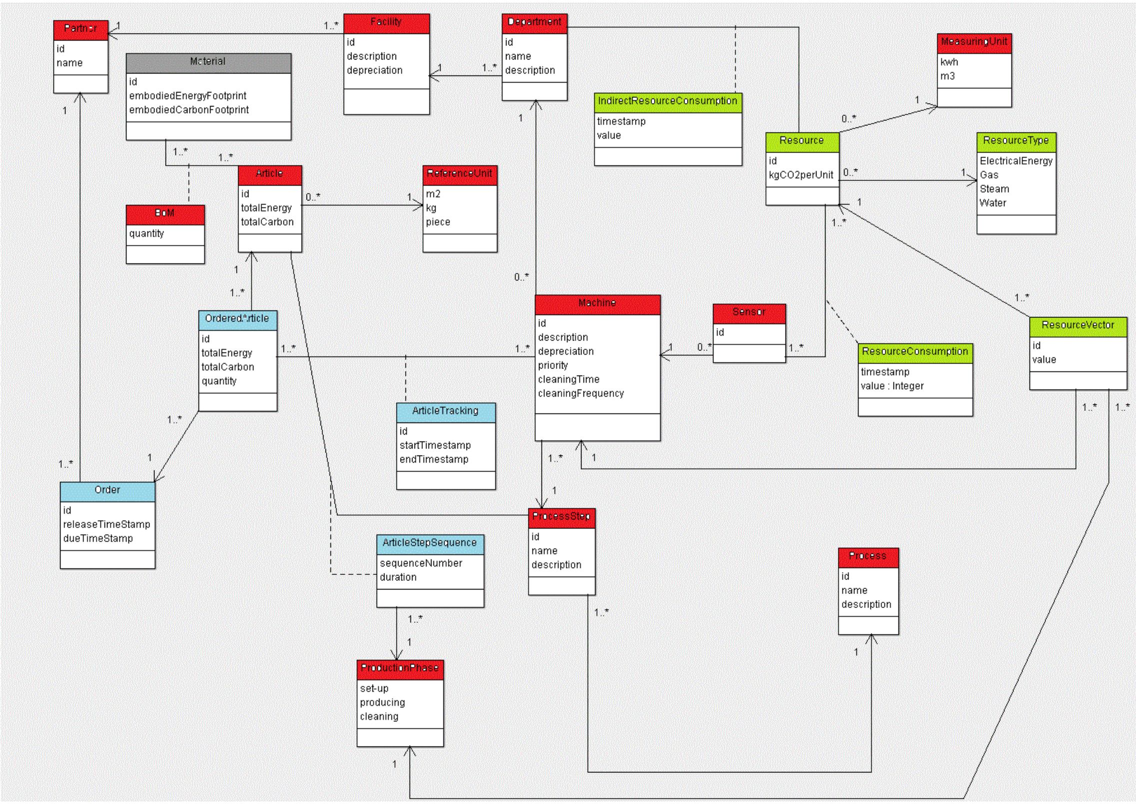

Figure D. 1: Data model integrating all information flows in Manufacturing

Table D.1: Entities in the Manufacturing data model

Data Entity	**Description**	**Flow**	**Source**	**Granularity Level**
Article	A list of articles that are produced. It has having an id, a ReferenceUnit (e.g., kg.), a totalCarbon and a totalEnergy attributes. The latter attributes, i.e. totalCarbon and totalEnergy, are aggregated values of historical data. The method of aggregation is irrelevant at this point of analysis, considering that there are various methods of such calculations (e.g. the sum of energy consumed by previous orders, over the quantities produced).	CI	ERP/MES	One record for each distinct partner
ReferenceUnit	An enumeration of all the types of the article reference units within the system (e.g. kg).	CI	ERP/MES	One record with an enumeration of all the types of the article reference units
Department	The departments that exist in a facility, having an id, a name and a description as attributes.	CI	ERP/MES	One record for each distinct department

Facility	The facilities used by a partner, having an id, a description and a depreciation attribute, i.e. the depreciation of energy consumption used for the construction of the facility.	CI	ERP/MES	One record for each distinct facility
Partner	This entity depicts every partner within a supply chain. Its attributes are a name and an id.	CI	ERP/MES	One record for each distinct partner
BoM	The bill of materials for an article.	CI	ERP/MES	One record for each distinct article and material
Machine	The machines existing in a department, having an id, a description, a depreciation (i.e. the depreciation of energy consumption used for construction of machinery), and the priority of the machine.	CI	MES	One record for each distinct machine
Process Step	The parts of a process. Every process-step has an id, a name and a description. Multiple process-steps make up a process.	CI	MES	One record for each process step
Process	The processes that take place within a facility, having an id, a name and a description as attributes.	CI	MES	One record for each process
ProductionPhase	ProductionPhase is an enumeration that defines all the possible production phases, i.e., set-up, producing, cleaning.	CI	MES	One record with an enumeration of all the types of the production phases
Sensor	The metering devices installed, having an id and a machineId.	CI	Sensors Infrastructure/ EMS	One record for each sensor with details regarding the monitored machine
MeasuringUnit	An enumeration that defines the possible measuring units of a resource (e.g. KWh).	CI	Sensors Infrastructure// EMS	One record with an enumeration of all the types of the production phases
OrderedArticle	Articles that have been ordered. Its attributes are an id, a totalEnergy attribute which is the consumed energy for the articles production and totalCarbon, which is the total carbon emitted for the production of this article. The latter fields are calculated for each ordered article individually by the ECMS.	TI	ERP/MES	One record per article ordered

Order	The orders placed for a specific partner. Its attributes are an id, the quantity, the dueTimestamp meaning the due-date and the releaseTimestamp.	TI	ERP/MES	One record per order
ArticleTracking	Tracks which ordered article passes through which machine. Its attributes are an id, a startTime and endTime.	TI	MES	One record per article and machine
ArticleStepSequence	ArticleStepSequence is an association class that maps articles on process steps and production phases. A set of instances from this class depicts the sequence of process steps from which the article passes through, and for each step at what phase of production (setting-up, producing, and cleaning). Its attributes are an id, a sequenceNumber which is the sequence number of a process step, the duration, i.e., an average time needed for an article in a process step in a specified production phase.	TI	MES	One record per article and process steps and production phase.
Resource	The non-renewable resources that are necessary to perform industrial operations; although a generic entity, in the current context it mainly refers to energy. Its attributes are an id, a resource type (e.g. electrical energy, gas), a measuring unit (e.g. KWh), and kgCO2perUnit, i.e. the value in kgs of carbon dioxide per measuring unit.	EC	Sensors Infrastructure/ EMS	One record per resource
ResourceConsumption	Maps the direct resource consumption s (i.e. energy consumption of production processes) to sensors having as attributes, a timestamp, and a value which is the amount of the consumed resource.	EC	Sensors Infrastructure/ EMS	One record per sensor and the selected time interval (e.g. one record per machine and second).
ResourceVector	A vector that holds a planned value of a resource required, for a machine over a specified production phase. Its attributes are an id and the planned value. The method of calculation of such values, again, is irrelevant at this point of analysis, considering that there are various methods of such calculations	EC	ERP/MES	One record per machine and production phase.
IndirectResourceConsumption	The indirect consumption of energy resources (i.e. energy consumption of non-production processes), having a timestamp, and a value as attributes.	EC	ERP/MES	One record per facility or infrastructure that its indirect consumption is

				measured (e.g. per department)
Material	The materials that make up an article, having an id, an embodiedEnergy and an embodiedCarbon attribute, i.e. the total energy consumed for material production.	PEIF	LCI/Internal systems for measuring carbon footprint	One record per material

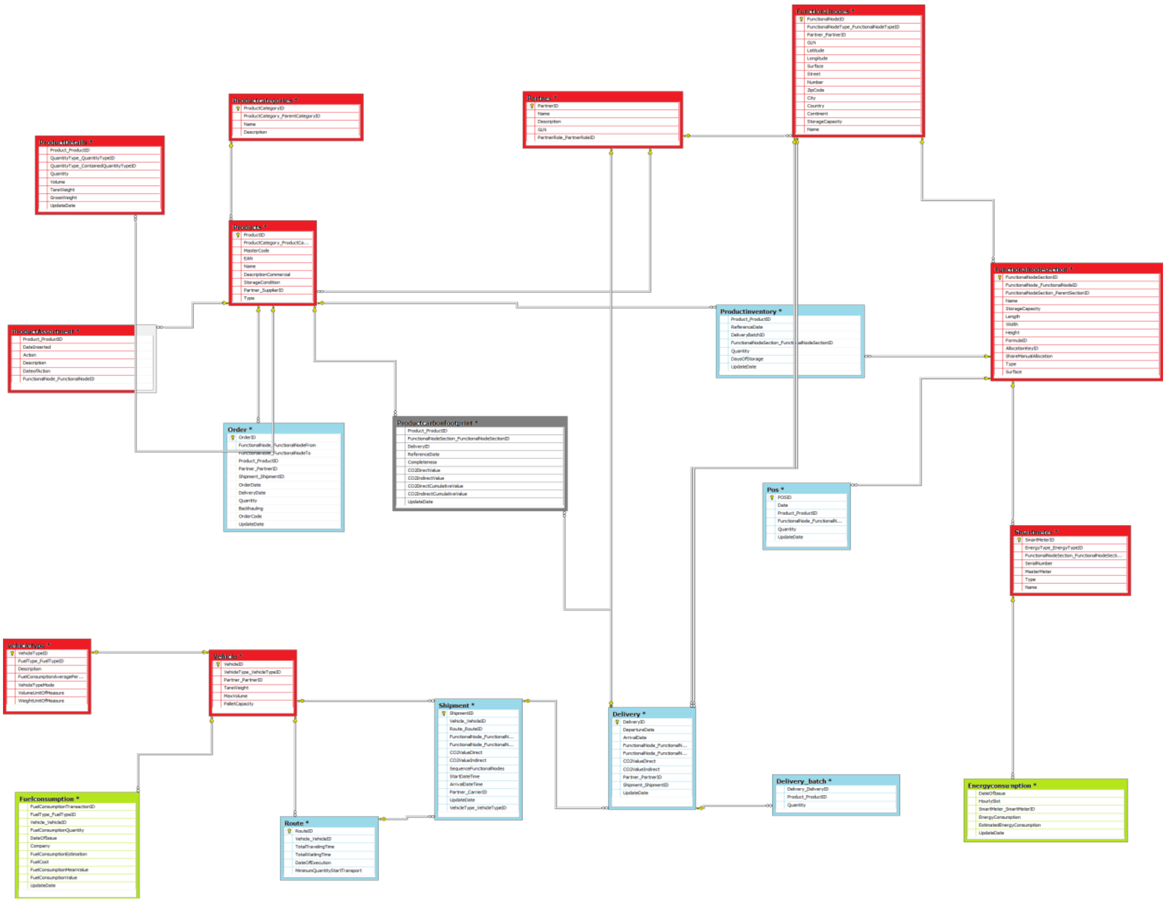

Figure D. 2: Data model integrating all information flows in Warehousing and Distribution

Table D. 2: Entities in the data model

Data Entity	Description	Flow	Source	Granularity Level
Partner	List of supply chain partners, e.g. list of supplies a retailer collaborates with or list of customers/retailers a supplier collaborates with	CI	ERP/WMS	One record for each distinct partner
Vehicles	A list of vehicles and other means of transportation used in shipments	CI	ERP/WMS	One record for each distinct vehicle based on the vehicle licence code
Vehicle Type	A list of available vehicle types. These types characterize each vehicle.	CI	ERP/WMS	One record for each vehicle type

Functional Nodes	A list of Warehouses and Stores (Functional Nodes)	CI	ERP/WMS	One record for each distinct warehouse/store
Functional Nodes Sections	A list of Warehouses and Stores sections	CI	ERP/WMS	One record for each distinct warehouse/store section
Product Categories	Tree structure of product categories in a flat file	CI	ERP/WMS	One record for each distinct product category
Products	The list of products with all the associative codes and product category	CI	ERP/WMS	One record for each distinct product. Products are unified by their barcode
Product Details	Some details related to the product characteristics (e.g. volume, weight, etc.)	CI	ERP/WMS	One record for each distinct product.
Product Assortment	A list of active product codes for every functional node	CI	ERP/WMS	One record per each store and product combination
Smart Meter	A list of the installed smart meters	CI		One record per each smart meter
POS (Sales)	The number of items sold from a specific store (functional node) on a specific date	TI	ERP	One record per product sold, per store, per day.
Shipments	Shipments from a warehouse to other supply chain nodes (customer WH or store)	TI	ERP/WMS	One record per shipment executed
Deliveries	Information on deliveries to a supply chain node (e.g. Warehouse or store). In case the data come from a retailer with central warehouse, then deliveries from warehouse to the stores doesn't need not be sent, as this is the same information as in the shipments file. Direct deliveries from suppliers to stores would need to be included.	TI	ERP/WMS	One record per delivery executed
Delivery_Batches	Information about the products included in each delivery and their respective quantities	TI	ERP/WMS	One record per product distribute via a specific delivery.
Route	The trip of a vehicle (an abstract path between two or more nodes)	TI	ERP/WMS	One record per route traversed.
Order	Information about orders	TI	ERP/WMS	One record per order code and product included
Functional Nodes Inventory Levels	The number of available items at each warehouse or store.	TI	ERP/WMS	One record per product stored per day at each functional node

Fuel Consumption	The fuel consumed (and the type) for the execution of a specific shipment	EI	ERP/WMS	The fuel consumption is related to a specific vehicle and report the consumption for a given time period.
Node Energy Consumption	The energy consumption consumed in a functional node (warehouse/section)	EI	Sensors/BMS	The energy consumption is stored on a daily basis and it is referred to each functional node separately.
Product Carbon Footprint	The product carbon footprint of a finished product.	PEIF	LCI/Internal systems for measuring carbon footprint	The product carbon footprint is referred to a specific product and it is related with the delivery batch.

Appendix E: ECMS System Components Design Principles

Table E.1: Energy and Carbon Management Systems Components and the Respective ECMS Design Principles

System Components	Design Principle
Energy Data Layer	The system should provide the ability to determine the available data and set up the respective interfaces with e.g. EMS, BMS and energy sensors.
	The system should allow the data provision scheduling by allowing user e.g. to define the frequency of updates for available data coming from energy consumption resources
	The system should manage the data received from the available data sources and parse, validate and clean-up them by perform a set of validations such as non missing measurement reads
Operational Data Layer	The system should provide the ability to determine the available data and set up the respective interfaces
	The system should allow the data provision scheduling by allowing user e.g. to define the frequency of updates for available data coming from user's ERP systems.
	The system should manage the data received from the available data Sources and parse, validate and clean-up them by perform a set of validations such as file availability, file structure/format compatibility and a variety of data validations.
	The system should provide interfaces that will expose the operational data layer to the rest of ECMS components.
Energy Sensor Monitoring	The system should configure the various energy meters in order to ensure for example that they report the results in the same measurement units and time frames.
	The system should manage the various energy meters in order to specify e.g. at which machine it is assigned.
	The system should manage (collect, process and store) the energy consumption data that comes from energy meters. The system should for example: the assignment of time stamps and energy values for each machine, the aggregation of such values (sum, mean, and standard deviation) per time interval (minute, hour, day); and the inspection of excessive energy consumption.
	The system should provide interfaces that will expose the energy consumption measurements to the rest of ECMS components.
	The system should provide and manage alerts e.g. by defining maximum (i.e. alert) energy levels per machine or process, generating alert reports and the user-defined actions triggered by the alert (e.g., machine shut-down).
Non-Sensor Energy Monitoring	The system should provide the ability of defining the type of secondary available data e.g. energy vectors per process, per facility

Energy Consumption and Carbon Footprint Estimator	The system should manage (collect, process and store) the energy and fuel consumption based on secondary data in order to enable a company to implement energy and carbon management
	The system should implement a business logic that will enable the calculation of the required Key Performance Indicators at the various levels of analysis.
	The system should provide the ability to a user to configure the KPIs calculation logic parameters.
	The system should implement a business logic that will calculate the different types of energy consumption e.g. direct vs indirect.
	The system should provide interfaces that will expose the estimation outcomes to the rest of ECMS components.
Transactions Flow Network Monitoring	The system should monitoring the daily activities (shipments, storage, production) and (b) supporting the calculation of the required KPI's for the different levels of analysis.
	The system should provide mechanisms that support the coordination of all workflows e.g. orders, deliveries, and shipments of the different partners in order to enable energy and carbon management in the supply chain.
	The system should supports the calculation of the required KPI's for the different levels of analysis.
	The system should provide interfaces that will expose the estimation outcomes to the rest of ECMS components.
Supply Chain Design and Modeller	The system should manage the data related to the organization structure and dependencies in order e.g. to define facilities, departments and supply chains.
	The system should support the modelling of the supply chain or production processes structure
	The system should support the decomposition of the supply chain or production processes structure to the required level of analysis.
	The system should support sharing mechanisms of existing supply chain or production processes structure information.
	The system should provide a collaborative environment for modelling and design in order to support the modelling of collaborative supply chains. **(Only Warehousing and Distribution Case)**
	The system should provide interfaces that will enable sharing of the supply chain or manufacturing processes structure with other ECMS components.
Report Generator	The system should provide a user the ability to view a set of predefined reports that cover the various ECM dimensions, Hierarchy and KPIs
	The system should provide a user the ability to create its own reports
	The system should support the rest of the components on presenting their results in the user e.g. create reports regarding the enterprise structure and the available resources handled by Supply Chain Design and Modeller
Collaboration	The system should provide a feature that the definition of new

Platform	partnerships and the terms of this collaboration and the management of existing ones **(Only Warehousing and Distribution Case)**
	The system should provide features that will enable various types of collaboration and information exchange levels **(Only Warehousing and Distribution Case)**
	The system should provide features that ensures data privacy e.g. security protocols implemented **(Only Warehousing and Distribution Case)**
	The system should provide data exchange mechanisms in order to facilitate information sharing **(Only Warehousing and Distribution Case)**
	The system should use standards for information sharing among supply chain partners in order to support Energy and Carbon Management in the Supply Chain. **(Only Warehousing and Distribution Case)**
	The system should incorporate a calculation method that supports monitoring across supply chain that will examine and make sure that the collaborative partners have adopted compatible LCA measurement model(s), therefore the calculation of direct and indirect emissions are managed uniformly. **(Only Warehousing and Distribution Case)**

Appendix F: Non-Functional Requirements

In summary, the evaluation of the artifact during pilot testing of the system in real-world settings shows that no technical problems were encountered that could diminish the pilot user experience and reduce the overall quality of the system. Moreover, the system was perceived as user-friendly and reliable, offering easy access to information and supporting efficient monitoring of energy consumption and carbon emissions. Also, the employees that used the system endorsed the system's reliability and quick response to requests. The users further claim that the system provides information that was unavailable before and can support the reduction of carbon emissions by enforcing the decision making process.

This section presents the non-functional requirements. Table 1 shows all the non-functional requirements that were analyzed before the pilot execution, as part of the pilot preparation task. These qualities have no actual quantitative measures (e.g. metrics) to be taken into consideration, since these are mostly qualities whose fulfillment is based on the decisions made during the design phase of the integrated system and its respective components. Table 2 shows the results of the analysis made in the non-functional requirements that a quantitative measurement can be applied. These qualities were measured in two different ways: through a stress test process, when the pilot systems were live and available and through constant monitoring, using log files and proper user feedback.

Table F.1: Non-functional requirements measured before the pilot execution

Non-Functional Requirement	No.	Description	Fulfilled?	Analysis/Comments
Deployment	NFR.1	Distributed components shall be communicate with a compliant W3C architecture (e.g. Message Oriented model, Service Oriented model or Resource oriented model)	Yes	All components have been designed to communicate using RESTful web services, that fulfil the W3C constrain mentioned by NFR.3
Interoperability	NFR.2	Individual components should be able to exchange information and use the information exchanged.	Yes	All components have been designed to exchange information with at least one other component (either directly or through the common database), and to use the information exchanged.
	NFR.3	The system should inform the partners about the minimum information resources required in order to produce accurate and meaningful measures.	Yes	All components of the system have been implemented so that they provide this kind of information to the partners.
Security/Privacy	NFR.4	The system should ensure authentication, authorization and integrity to protect from unauthorized exposure of information	Yes	The users of the system are required to log in, before being able to access any of the system components and services.

	NFR.5	The system should conformed with specific European market regulations and Fair Trade Acts.	Yes	This is guaranteed by the design of the different components of the system, as these are depicted in the overall architecture.
Scalability	NFR.6	The system should be able to scale up horizontally and vertically by increasing hardware resources	Yes	All components have been designed, so that they can scale up as more hardware resources are provided to them.
	NFR.7	The system should be able to manage multiple suppliers and retailers and other roles that participates in the supply chain context (e.g. 3PL)	Yes	Both the database and the components of the system have been designed to be able to handle more than one partner (each one with a possibly different role) that participates in the supply chain context.

Table F.2: Non-functional requirements measured during the pilot execution

Non-Functional Requirement	No.	Description	Fulfilled?	Metric	Value	Process / Comments
Availability	NFR.8	No downtime is expected for activities like database, upgrades and backups	Yes	Number of times system was unreachable	0	This is guaranteed by the host that provides the pilot environment. During the piloting there were no downtimes of the system
Fault Tolerance	NFR.9	The system should continue operating properly and recover without loss of data in the event of failure of individual components.	Yes	Number of times the system failed because of an error	0	This is ensured by the loosely-coupled architecture of the system. Even if a component created faulty behavior, the rest of the system could continue functioning. No problems were encountered during the pilots
Performance	NFR.10	Every component of the system should support more than 250 of simple queries per minute	Yes	Requests per second	200+	This was measured by a custom Java application that executes 5 simple queries per second (e.g. retrieve all functional nodes),

						and another one that makes 200 HTTP requests per second to different components (i.e. pages) of the system.
Response Time	NFR.11	No more than 10 seconds for typical queries and 30 seconds for custom queries considering that the central database is being queried	Yes	Response Time in ms	<3 sec	This was measured by a custom Java application that executes 10 typical queries (e.g. retrieve all functional nodes) and custom queries (e.g. retrieve all products in a functional node) per second, measures the response time for each one of them, and calculates an average value. The actual database load during piloting was less than the stress tests conducted above.
	NFR.12	Every component of the system should periodically report to the Administrator its average and maximum response time regarding the Interfaces it controls.	Yes	Data Availability	No misses	All components are required to log their response times. All the data was recorded successfully at their appropriate log files.
Robustnes s	NFR.13	The system components should be able to recognize invalid data provided through an interface and response back with an informative message	Yes	Graceful handling of errors / Total number of errors	20/20	All components are required to display informative error messages. In our trials, all known error and error handling code has been tested successfully. During piloting, no unhandled errors were reported (like system crashes, stack traces etc).