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A hierarchical approach for evaluating energy trade-offs in supply chains

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ABSTRACT

Supply chain design and operational decisions may impact the energy needed to keep the products flowing through to the customers. It is a challenge to determine the energy consumption and even more challenging to understand the impact of design and operational decisions on the energy consumption along the supply chain. This paper presents a hierarchical simulation based approach for estimating the energy consumption to keep the products flowing through a supply chain. System dynamics simulation is used at a high abstraction level to understand the major factors that may affect the energy consumption. Discrete event simulation is then used to delve down in detail for evaluating the critical stages in the supply chain. A case study for a closed loop supply chain of forklift brakes is used as an example of application of the approach.

1. Introduction

A number of progressive companies are making conscious efforts for reducing environmental impact of their operations. These companies obtain a competitive advantage towards customers in addition to making a contribution to a more sustainable future. An example from food and service industry is provided by the award winning restaurant in Sweden called MAX. They reported that their efforts for evaluating and improving their product value chain led to a reduction of their CO_2-emmisions by 44% between 2007 and 2008 (MAX, 2008). Market research shows that 13 times more customers relate the MAX brand to environmental friendly products compared to their main competitor. MAX's sustainability manager states that the latter figure is not the result of an increase in traditional marketing, but derives solely from communication of their products' environmental footprint.

Matthews et al. (2008) highlight the importance of determining the carbon footprint across the supply chain and across the life-cycle. They recommend that the firms consider the life-cycle footprints from the outset, and “allow the largest sources of carbon emissions along the supply chain to be targeted first and most cost-effectively.” Hertwich and Peters (2009) stress that indirect impacts in the supply chain are more important than the direct impacts in the household in their analysis of carbon footprint of nations. Weber and Matthews (2008) show that about 30% of the carbon footprint of U.S. household consumption is outside the country, that is, the impact is in the international supply chains. These articles stress the importance of consideration of carbon footprint of the entire supply chain, in particular, the importance of including the international parts of supply chain.

A large contributor to the carbon footprint of a supply chain is the energy consumed in manufacturing and logistics. Ngai et al. (2012) identify control and reduction of unnecessary energy and utility consumption as one of the major ways to reduce greenhouse gases. This paper focuses on the energy consumption across a supply chain and presents an approach for evaluating options for reduction efforts and trade-offs related to energy use.

Calculation of energy use and emissions for a product across the supply chain can be challenging since almost all nodes and links across the supply chain serve multiple products. The energy use and emissions from manufacturing and logistics facilities may need to be allocated to determine the amounts for a specific product. Use of engineering models has been recommended to separately estimate the energy use for each product to avoid allocation (WRI/WBCSD, 2011). This paper presents an approach that uses engineering models, specifically simulation models of different paradigms, to calculate energy use for selected products across their supply chain.

The presented approach helps identify the largest consumers of energy along the supply chain at the outset using system dynamics modeling and then explore cost effective strategies for the largest consumers using discrete event simulation. Furthermore following the recommendations in the above mentioned literature, our proposed approach includes consideration of the entire supply chain including international segments if present as part of the configuration alternative.

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The next section provides background information on different simulation paradigms and on hierarchical levels in supply chain. Section 3 briefly reviews related work. The proposed approach is presented in Section 4 followed by a case study in Section 5 for demonstrating the application of the approach. Sections 6 and 7 describe the implementation of key steps of the approach for the case study. Section 8 concludes the paper and includes potential future work.

2. Background

The proposed approach in this paper utilizes models of different simulation paradigms as appropriate for the level of detail in the supply chain hierarchy. The following sub-sections briefly define the simulation paradigms and supply chain hierarchical levels.

2.1. Simulation paradigms

Simulation techniques can be classified using different perspectives. With the perspective of modeling of time, they can be classified as continuous and discrete. From the perspective of representation of the underlying phenomenon, they may be classified in four paradigms that admittedly have some overlaps (McLean et al., 2012, p. 20–29): system dynamics (SD), discrete event simulation (DES), agent-based simulation, and physical-sciences-based simulation. We briefly describe the four paradigms below with a bit more detail for SD and DES as they are used for the case study in later in this paper.

2.1.1. System dynamics (SD)

SD modeling and simulation, by design, is aimed at modeling systems at high level of abstraction for supporting high level decision making. It has been applied to study a wide range of systems including industrial, social, environmental, financial, and socio-political systems, and their combinations. While generally used to model large systems at high abstraction levels, the strength of modeling feedback loops also allows the technique's applications for control policies of small electro-mechanical systems.

Originally developed by Forrester (1958) to analyze manufacturing supply chains systems (then called industrial production systems), SD simulation is suited for studying behavior of large systems. It focuses on modeling causal relationships between key aspects of the system operating under governing policies, especially feedback loops that form beneficial or vicious cycles and determine the overall system behavior. It uses the continuous paradigm for representing time.

The technique utilizes causal loops for conceptual modeling that are enhanced into stock-and-flow diagrams for setting up the framework. The computer implementation then converts the causal and stock-and-flow relationships into differential equations that are used to calculate the change in system parameters over the simulated time horizon. The changes in key parameters of interest define the system performance over time. Sterman (2000) provides a detailed description of system dynamics simulation and guidance for its use for many applications.

2.1.2. Discrete event simulation (DES)

DES is suitable for modeling system operations to evaluate system configurations and resource allocations in order to achieve desired system performance or to investigate causes of less than desired performance. It is generally used to model systems at medium to low levels of abstraction. DES models are generally used for planning purposes, however, there are increasing instances of their use in near real-time decision support systems, particularly in manufacturing.

In DES, the operation of a system is represented as a chronological series of events. As the name indicates, it uses discrete event paradigm for representing time – the simulated clock time jumps from one event of interest to the next event of interest without going through successive unit increments.

Discrete-event simulation models may be developed using one of two major views: process view or event view. Process view essentially uses flow charts of process of interests and models them using corresponding simulation software features. The process view is also referred to as entity view or transaction view as it models the process that entities (or transactions) of interest go through in the system. The event view model uses the actions that happen following an event. Consider for example a part being processed through a machine shop. The process view may model the flow of the part going from one machine to the next and the processing that happens at successive machine until its completion. The event view may model events such as arrival of the part at a machine that triggers the start of its processing and schedules the processing completion event. The processing completion event in turn initiates the part's transfer to the next machine. Schriber et al. (2012) explain the inner workings of DES and the implementations in a few commercial DES software packages.

2.1.3. Agent-based simulation (ABS)

ABS is suitable for modeling systems where the behavior is determined by the interactions of a large number of independent entities. Example applications include modeling the behavior of a crowd of people affected by an incident, and modeling the spread of a pandemic flu based on the behavior of individuals in the population in the affected area. ABS utilizes a decentralized representation of systems and allows the system behavior to be determined based on defined behaviors of a number of modeled agents. ABS may follow the discrete event paradigm or the continuous paradigm for time representation or they may utilize the hybrid form, i.e., using a combination of discrete and continuous representations. A good overview of agent based simulation is provided by Macal and North (2011).

ABS has been used for modeling supply chains with each of the nodes represented as a separate agent. Such representations with only a few agents may be hard to differentiate from a DES representation of the system being modeled.

2.1.4. Physical-science-based

Physical-science-based simulations utilize scientific knowledge, e.g., the laws of physics or mathematical models of observed phenomena to study, understand, or predict the behavior of physical systems. Physical systems can range from modeling a single entity, e.g., in the study of motion of a bullet, to modeling a complex set, e.g., the behavior of multiple organisms, crowds, or global climate.

Physical-science-based models may use mathematical equations and schematic diagrams as conceptual models. These models typically utilize differential equations based on laws of physics that model such factors as mechanical dynamics and statics, material behavior under stress and impact, and fluid dynamics. They are generally used for modeling at detailed level, that is, at low abstraction level, such as, equipment and equipment component behavior, and behavior of built structures when subjected to explosions in close proximity. A number of examples of physical-science-based simulation are provided in Engquist et al. (2009).

2.2. Supply chain hierarchical levels

We propose to analyze the supply chain impact on environment in a top–down manner along the supply chain hierarchy. While a number of metrics may be used for measuring impact on environment, the metric of interest for this study is energy consumption. The supply chain hierarchy is used to allow estimating metrics at a gross level and delve down to finer levels when needed due to importance of certain nodes or specific interest in some nodes. The idea of hierarchical representation of supply chain processes has been employed in Supply Chain Operations Reference (SCOR) model (Supply Chain Council Inc., 2010). Indeed SCOR model has been used as an input for development of hierarchical supply chain ontology architecture (Jian and Jianyuan, 2011). We propose a hierarchy based on physical components of a supply chain to support our objective of successively modeling selected components with increasing fidelity. While our proposed decomposition is focused on physical components, we include modeling of associated processes for the evaluation of impact of operations on the environment using identified metrics such as electricity consumption.

The important nodes in a supply chain may be identified as those that have a large impact on the performance of the total system. Supply chains may be viewed as being comprised of manufacturing nodes, logistics nodes and links. The proposed supply chain hierarchy levels for manufacturing nodes, logistics nodes and links are shown in Table 1 below. The idea of successively looking at more detailed level is similar to the idea of layers of supply chain used by Sarkis (2012). The supply chain hierarchy levels for manufacturing are based on hierarchical modeling levels proposed by McLean and Leong (2002), albeit we cover a smaller range. We have defined the hierarchical levels in logistics nodes column guided to some extent by the hierarchy of decision problems presented by van den Berg and Zijm (1999). Similarly, we have defined the levels for the logistics links column drawing ideas from the intercity freight transportation system model structure developed by Fernandez et al. (2003). The hierarchical levels defined in the table are for the express purpose of modeling selected parts of the supply chain at increased levels of detail in the interest of efficiency of the modeling process.

3. Literature review

This section successively and briefly reviews prior related work in the following areas relevant to our effort: energy consumption reduction in supply chains, SD simulation for sustainable supply chains, DES for modeling environmental impacts of manufacturing, and hybrid SD and DES models for the same purpose.

World Resources Institute (WRI) and World Business Council for Sustainable Development (WBCSD) have developed a series of Green House Gases (GHG) protocol standards that include guidance for calculating GHG inventories. The value chain standard focuses on the factors contributing to GHG inventory across the supply chain including energy use (WRI/WBCSD, 2011). It identifies energy reduction as being important for a company since energy taxes or regulations may significantly increase its purchased cost of goods or components. Companies are also encouraged to reduce energy during use phase and end-of-life phase by marketing less energy intensive products and advising customers on efficient use and disposal. Calculating scope 3 inventory is presented as one of the ways to identify where the largest energy, materials, and resource use occurs within the supply chain.

Reduction of energy consumption across the supply chain is one of the motivations behind Green Supply Chain Management (GrSCM). GrSCM's overall goal is to integrate environmental considerations across all supply chain management functions including supplier selection, manufacturing, distribution, and end-of-life management (Linton et al., 2007). GrSCM includes green product design and a closed loop product return processing. The measurement of performance of GrSCM is challenging (Sundarakani et al., 2010).

One of the key performance measures of interest for evaluating environmental consideration across the supply chain is energy consumption. Sundarakani et al. (2010) identify energy use as one of the driving forces of green supply chain in their long range model of a closed loop supply chain. GrSCM can reduce energy consumption, reduce waste and pollution, reduce carbon emissions, and thus conserve natural resources (Parry et al., 2007).

Cholette and Venkat (2009) study the energy and carbon emissions associated with the distribution part of the wine industry supply chain. They conclude that supply chain design can have a significant impact on the energy consumption and carbon emissions. Lam et al. (2010) use reduction in energy use as the primary motivation for development of a regional energy clustering algorithm that forms energy supply chain clusters. The algorithm identifies clusters with minimum total carbon footprint and reduced energy waste.

Quariguasi Frota Neto et al. (2008) study tradeoffs in supply chains using a technique that combine multi-objective programming and data envelopment analysis. They present a case study of European paper and pulp industry and show the usefulness of the model results that are non-intuitive. Smith and Ball (2012) develop guidelines for modeling material, energy, and waste flows in a manufacturing facility to identify opportunities for environmental efficiency improvements.

Weinert et al. (2011) propose EnergyBlocks methodology for accurate prediction of energy consumption in production systems. The capability is used to evaluate alternatives for reducing energy consumption in a production system. Adaptation of production schedule for the specific case study is shown to reduce the scheduled time by 22% and energy consumption by 11% compared to the strategy of assigning all the process steps to the machine with least energy consumption.

Life cycle assessment (LCA) has been a major approach for evaluating environmental impact and total use of resources and energy during a product life cycle (Ness et al., 2007). It is standardized in ISO 14040 and ISO 14044. LCA is a static modeling approach that aims to cover the total product life cycle by collecting inventory data of the emissions from all processes and life stages for a specific product and service. Common assessment methods are greenhouse warming potential (GWP), acid potential (AP), eutrophication, and human toxic effects. Simulation can be used to replace the static modeling approach used in LCA to get a more detailed and dynamic model of the system (Thiede et al., 2013).

One benefit of using simulation modeling approach in comparison to assessing environmental effects using conventional LCA

Table 1
Hierarchical levels in supply chain.

Level	*Manufacturing Nodes*	*Logistics Nodes*	*Logistics Links*
0	Supply chain	Supply chain	Supply chain
1	Manufacturing plants	Distribution centers	Multi-Modal Routes
2	Lines or areas	Storage areas	Single-mode Routes
3	Cells or workstations	Storage systems	Route segments
4	Machines and equipment	Storage and Material handling equipment	Logistics vehicle (truck, train, ship, plane, etc.)

methods is the time aspect and the dynamic behavior of a supply chain in action. The main problems associated with traditional LCA analyses are (Reap et al., 2003):

- The use of lumped parameters and site-independent models.
- Static in nature and disregard of the dynamic behavior of industrial and ecological systems.
- Focus only on environmental considerations, not economic or social aspects.

During model-building and analysis of LCA in combination with DES in Ingvarsson and Johansson (2006), Alvemark and Persson (2007), and Persson and Karlsson (2007) it was recognized that the supply chain and its actors do have a major role in influencing the environmental effects both positively and negatively. By integrating the life cycle of the product at hand utilizing SD these aspects could be more clearly shown and analyzed.

SD has been used to study sustainability issues in manufacturing at high levels of abstraction for decades. Ruth (1995) used STELLA, one of the early SD software, to assess the US iron and steel industry for 1987–2027 period and conclude that unrealistically high rates of iron and steel recycling will be needed to reduce energy use and emissions in the long run if there is even a modest increase in raw steel production. SD simulation has been identified as an appropriate modeling tool for sustainable closed loop supply chains and used to study sustainability in electrical and electronic equipment supply chain by Georgiadis and Besiou (2008). Kumar and Yamaoka (2006) also use SD to study the closed loop supply chains of U.S. and Japanese auto industries and conclude that government regulations can have a large impact on the reverse supply chains. Vlachos et al. (2006) use SD to study closed loop supply chains for capacity planning and take environmental issues such as legislation and green image into account. Trappey et al. (2012) used SD to identify sustainable product redesigns and evaluating the carbon footprint during the product lifecycle. While the authors of the above referenced papers address sustainability issues, they do not use their models to calculate the energy consumption or potential reductions in energy use. In the SD model presented in this paper, we explicitly include the energy consumption at each stage of the supply chain and consider alternatives for potential reductions in energy use.

Efforts on modeling environmental effects in DES in recent research have been summarized by Herrmann et al. (2011). They utilize an energy oriented simulation model developed using AnyLogic to identify potential energy savings in manufacturing systems. The model includes representation of auxiliary services such as compressed air. They identify opportunities for energy reduction of up to 7% in an aluminum die casting case study and of up to 26% in weaving mill case study.

There are few efforts that use a hybrid SD and DES approach for modeling supply chains. In their survey of 127 papers devoted to simulation modeling of supply chains, Tako and Robinson (2012) classified only three papers that used the hybrid SD-DES approach for the purpose. Lee et al. (2002) identified presence of continuous and discrete phenomena in supply chains and employed the hybrid approach to show its applicability. Reiner (2005) utilized the hybrid approach to evaluate supply chain process improvements under consideration of customer orientation. Venkateswaran and Son (2005) used the two techniques together for hierarchical production planning with a SD model for enterprise level planning and a DES model for shop floor scheduling. The two models were integrated using the high level architecture and traded data during run time. It should be noted that some of the recent commercial software provide the capability of using multiple simulation paradigms within one model and hence facilitate run-time integration. For example, Anylogic (XJ Technologies Company Ltd., 2012) and Simio (Pegden and Sturrock, 2012) allow combining SD, DES, and agent-based paradigms. Our approach in this paper does not require such run-time integration as we use SD modeling first to get insights that we explore further using DES models.

4. Approach

The approach presented in this section is brief with the assumption that the analysts use well proven simulation methodologies for individual simulation studies for the respective paradigm. For example, methodologies for DES are described in Banks et al. (2004) and Law and Kelton (2000). The methodologies include collection and analysis of input data, modeling using the selected simulation paradigm, and analysis of simulation outputs. For our selected domain, this means that analysts need to be well versed in collection and representation of information for energy consumption in manufacturing, such as those described in Skoogh et al. (2011). Similarly, the expertise needs to include modeling and output analysis using the different simulation paradigms. For example of use of SD for sustainable manufacturing see Kibira et al. (2009), and for use of DES for production flow studies with focus on environmental impact see Andersson et al. (2012).

Our approach follows a top–down analysis path. It is initiated with the supply chain level and delves down in details as warranted by the results of the top level analysis. That is, after the first high level analysis, the nodes with opportunities for improvement will be analyzed at next level of detail. The opportunities for improvement may be identified based on the energy consumption associated with different nodes or based on the ability to control the particular nodes or their respective constituents. The approach is shown in Fig. 1 and can be briefly presented as below:

Step 1. Create an SD model to analyze the supply chain across life cycle at high level. The high level model utilizes supply chain node level data such as energy consumption and emissions for the factories and logistics links that comprise the chain. At this stage some of the data may be estimated or be based on data available for generic facilities in on-line data bases. The model at this level should be developed to support high level tradeoffs such as alternate supply chain configurations. The high level results should be validated to the extent possible via review with relevant experts and decision makers.

Step 2. Utilize the SD model for any tradeoffs at a high level. This may include alternatives for supply chain design and operational policies. Supply chain design alternatives may include scenarios with different number and location of suppliers. Supply chain operational policy alternatives may include scenarios with different inventory policies and frequency of planning updates. The tradeoffs may be limited based on the relationships between the organization conducting the analysis and the organizations responsible for respective nodes in the supply chain. Once the supply chain design and operational policies have been settled through the use of SD simulation, proceed with the next step to analyze at a more detailed level.

Step 3. Identify the nodes and links with a high apparent opportunity for reduction of energy consumption through exploration of the model results and industry and literature information. If the identified node is a complex operation, a more detailed system dynamics model may be built and analyzed to identify the facility or area that provides the highest opportunity among the components of the operation. Again, the tradeoffs may be limited based

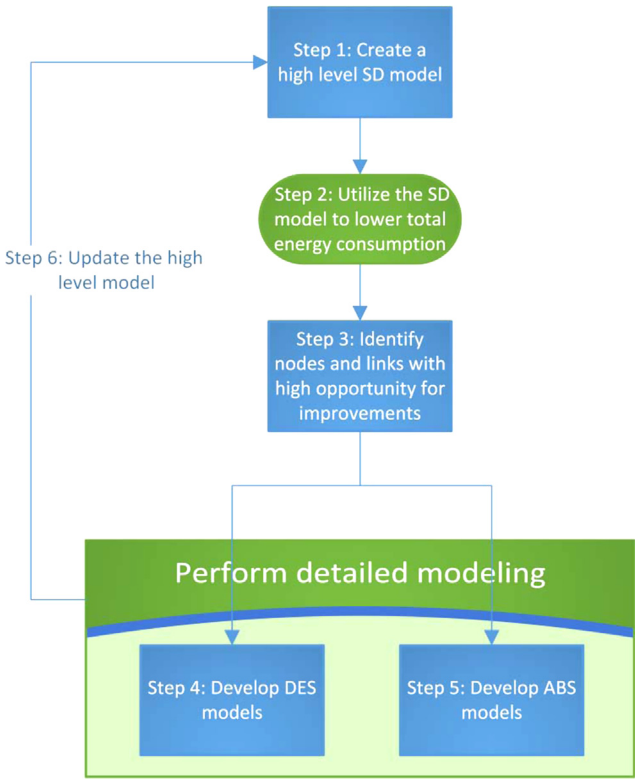

Fig. 1. Schematic diagram of the approach.

on the relationships between the organization conducting the analysis and the organizations responsible for respective nodes in the supply chain.

Step 4. Develop DES models for the identified node in step 3. A DES model gives the capability to analyze the production at a lower level than the overall SD model. The level of details in a DES model is almost unlimited, which makes it possible to study processes in very close detail and investigate uncertain behaviors. The DES model should be used for tradeoffs at detailed level such as alternate operational policies within the facility or area.

Step 5. Develop an ABS model to explore the tradeoffs if the identified opportunity is in an area that involves interactions with multiple people, in particular people from different organizations or customers. For example, an ABS model may need to be developed for evaluating incentives for customers for operating the product in a manner that reduces emissions or to encourage recycling.

Step 6. Update the high level SD model with the refined information acquired from the detailed level models once the issues have been analyzed. This will allow quantifying the impact of changes made at the detailed level on the overall supply chain.

The above steps may be iterated through successively to support a continuous improvement effort and to incorporate changes in the configuration of supply chain and its components. In each iteration, the next best opportunity should be addressed for reducing the impact of supply chain operations on the environment, or in this case, for reducing the energy consumption.

The approach, summarized in Fig. 1, allows flexibility in terms of use of models and interactions among them. Models at different levels of detail across the hierarchy may be loosely or tightly coupled as demanded by the issues being analyzed. The next section presents a case study that demonstrates the application of the approach.

5. Case study overview

To demonstrate the proposed approach from Section 4, a cradle-to-cradle supply chain system for a forklift brake lifecycle is used. We used the forklift brake system supply chain for the case study primarily due to following three reasons:

1. The availability of data in Life Cycle Inventory (LCI) databases for the materials used in forklift brake systems is better in comparison to other products.
2. The complexity of the lifecycle is relatively simple and in a closed loop in comparison to, e.g., consumer products.
3. The research team has access via industrial interactions with mining, forklift brake system production, forklift use, and recycling organizations in the particular supply chain.

The forklift brake system supply chain located primarily in Sweden is analyzed for its energy consumption and associated tradeoffs. The scope of the supply chain goes from cradle to cradle, that is, a closed loop supply chain starting from steel production, running through manufacturing and use phase, and ending with recycling of used brakes to the steel plant is considered. Fig. 2 shows a representation of a general supply chain in the context of a forklift lifecycle. The successive nodes in the modeled supply chain are listed below:

1. Iron ore mine
2. Steel plant
3. Brake component suppliers
4. Brake manufacturer
5. Forklift manufacturer
6. Industrial user of forklifts
7. Disassembler (recyclable steel components sent back to steel plant as raw material to reduce the need for mined iron ore)

6. Top level analysis using SD model

The implementation of the approach presented in the previous sections starts with step 1 involving the development of an SD model of the supply chain at a high level of abstraction. The data for the logistics and production nodes in the supply chain was gathered from multiple sources including industry inputs, databases, and literature. The first subsection describes the assumptions and limitations based on the data used for the SD model while the second subsection describes the model itself. The third subsection presents sample results from the SD model.

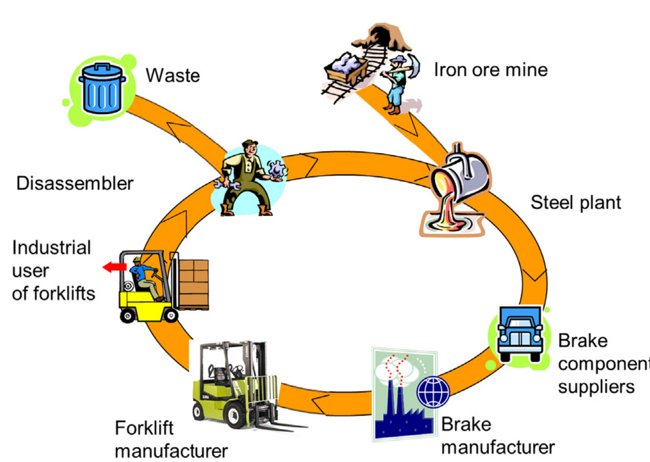

Fig. 2. Life cycle of a brake-set.

Subsections 6.4 and 6.5 demonstrate steps 2 and 3, respectively, of the approach with explorations of potential reductions in energy consumptions at various nodes in the supply chain and the use of the model for exploring trade-off between energy consumption and cost.

6.1. Assumptions and limitations for the SD model

The assumptions and limitation for the SD model based on the data gathered are listed below. The assumptions affecting all the nodes in the supply chain are listed first followed by the assumptions in the sequence of the nodes in supply chain, starting from the iron ore mine and going through the entire closed loop to recycling of the brake system components.

1. The overhead energy and emissions are allocated to the products based on product weight. A number of other allocation criteria such as machine hours, volume, pallets assigned for storage, number of shipments, and person-hours used for production could have been used. Our team considered product weight as the most representative criterion since it influences the volume, effort for internal material handling, and energy used for cooling and heating the internal environment among other factors.
2. All nodes use an inventory replenishment policy based on reorder level. The replenishment order quantity is the maximum of the minimum order size and the difference between current inventory and an order up to level.
3. It is assumed that the steel plant takes iron ore as input and provides steel as output. That is, it includes facilities for successively producing sinter iron, pig iron, and then steel. Also, the production is primarily based on iron ore input with partial input of scrap steel.
4. The brake manufacturer receives steel and a few machined steel products from different suppliers. Machined steel products are further processed at the brake manufacturer site and hence categorized as incoming raw material. For ease of calculation, all items categorized as raw material are assumed to be coming from one steel plant. Products that are assembled without any further machining are categorized as components for the brake assembly and modeled separately.
5. The energy use and emissions at the suppliers of components for brake-set, at forklift assembly, and at forklift disassembly operations have the same profile as the brake-set manufacturer itself and are proportional to the weight of steel in the product. This includes the energy use and emissions for production activity, storage area, and overheads such as heating and cooling for the facility. The assumption will hold for nodes where the production for the brake-set as a percentage of the entire production is roughly the same ratio as for the brake manufacturer. For a first high level model the assumption is not viewed as a major limitation.
6. There is a 5% scrap generated at the brake manufacturer that is sent directly to the steel plant to be used as raw material for steel production.
7. There is no reuse of the brake components. The steel components of the brakes are separated during disassembly of an end-of-life forklift and sent as scrap steel to be used as raw material for steel production.
8. The disassembly process sends 5% of the material to landfill. The energy consumed and emissions in the transportation of such material to landfill is assumed to be negligible for the purpose of the high level model.

The major data items and their sources are summarized in Table 2. Please note that energy usage figures shown in the table include energy required for internal and external processes and overhead allocated to production area and in turn allocated to brake-sets. The energy used for storage areas is calculated separately based on energy use allocated to storage area and on the amount of inventory for brake-sets. The emissions figures include those for internal and external processes and for the production facility allocated to brake-sets.

6.2. SD model description

Fig. 3 shows an edited view of the primary part of the SD model developed using Vensim. All the information arrows have been removed from the primary part of the model to facilitate understanding. As may be noted from the figure, the model is primarily comprised of stocks and flows, with stocks representing the inventories along the supply chain and the flows representing

Table 2
Major data items in brake system supply chain and their sources.

Supply Chain Node/ Link	*Major data item(s)*		*Source*
	Energy per brakeset produced (MJ)	*Emissions per brake-set produced (Kg CO_2 eq)*	
Iron mine	1819	5.73	Ecoinvent (Ecoinvent, 2012)
Steel plant	10,003	4.88	Ecoinvent
Suppliers (large component)	167	0.24	Projections based on data for brake manufacturer
Suppliers (other components)	61	0.09	Projections based on data for brake manufacturer
Brake manufacturer	533	0.77	Data collection at site of energy use and emissions in multiple categories including production, external processes and overhead
Forklift assembly	169	0.24	Projections based on data for brake manufacturer
Disassembly	337	0.49	Projections based on data for brake manufacturer
Other data categories	*Data Items*	*Value*	*Source*
Forklift use	Energy use (MJ/h)	0.58104	On-line source
Forklift use	Hours per month	300	Industry source
Transportation between nodes	Energy use (MJ/kg/km)	0.00279	Ecoinvent
Transportation between nodes	Distances in km	From-to distances ranging from 50 to 1500 km	Actual distances between the supply chain nodes

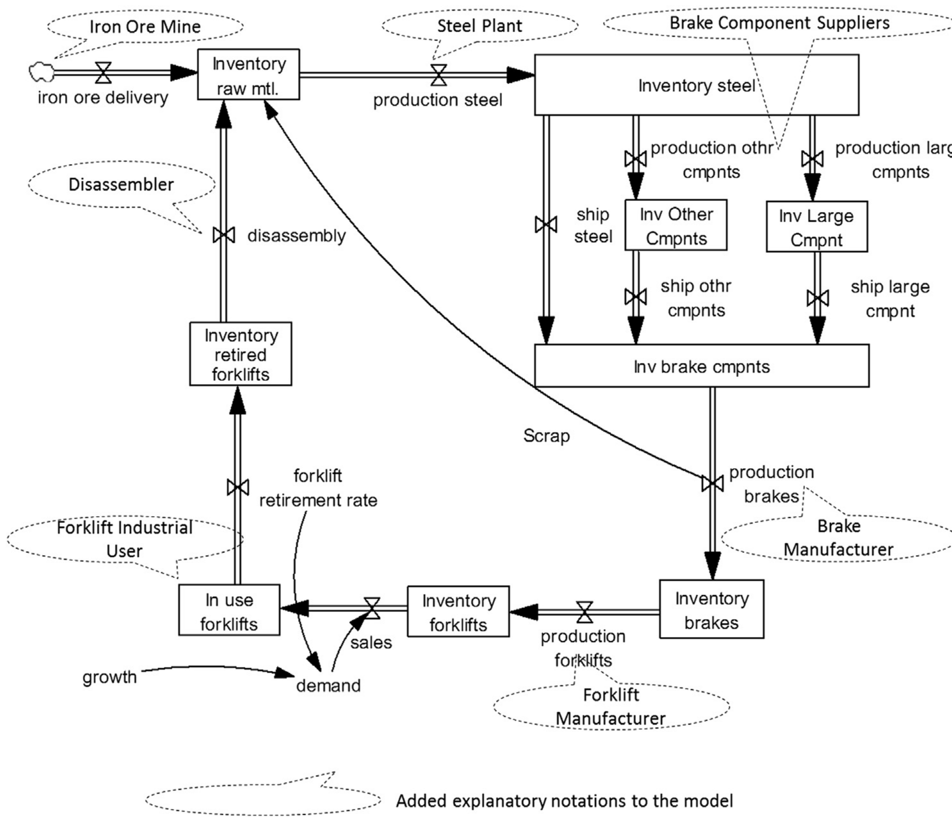

Fig. 3. Representation of the supply chain using system dynamics with added notations to identify the modeled seven nodes.

the conversion and logistics processes. The volumes of the flows for conversion of the product at manufacturing nodes along the supply chain are equated with logistics flows to determine the impact of the logistics activities. This representation thus assumes that the production and logistics transfer batches are the same and further they both equal the monthly volume at successive stages. The supply chain is driven by the demand signal, which is composed of a replacement component for forklifts being retired after completing their useful life and a growth component. The demand signal cascades through the supply chain with actual flows based on the replenishment order sizes at successive stages.

The model uses one brake-set comprising of two front and two rear brakes and wheels as the functional unit of analysis for determination of the carbon footprint. At each manufacturing node the following environmental factors are modeled:

- Energy consumption in production
- Energy consumption for storage of inventory at the location
- Emission in production activity

In addition, for each transfer between the manufacturing nodes, the following factors are modeled:

- Energy consumption in logistics
- Emission in logistics activity

6.3. SD model results

Execution of SD model provided information on the contribution to the energy consumption from different parts of the supply chain. Fig. 4 shows the variations in supply chain energy consumption over a 10 year period. It shows the stacked contributions of each of the three phases including cradle-to-gate, use phase, and end-of-life. For ease of presentation, the value for end-of-life phase is placed at the bottom, the value for use phase is added on top of it, and the value for cradle-to-gate phase is added last and is hence on the top. The contribution of end-of-life phase is quite small and hence the line representing the additional contribution from this phase runs quite close to the horizontal axis barely showing the contribution of the use phase. This stacking order allows showing the stable trends for the end-of-life and use phases and highlights the volatility in cradle-to-gate phase. The variations in the cradle-to-gate phase energy consumption are driven by the replenishment policies that initiate production approximately every other month to replenish the inventories due to demand traveling across the supply chain.

Fig. 5 shows the contribution of different life cycle phases to the energy consumption using a one year period value that is calculated as an average over the 10 year data. Note that the value is represented in Gigajoules (GJ) in this figure. It is clear that the cradle-to-gate phase has the largest energy consumption among the three major phases of the life cycle.

The results for monthly and yearly volumes from the SD model were reviewed against available data to ensure that the model outputs are within expected ranges. The model was considered suitable for use in the application of the approach.

6.4. Supply chain configuration tradeoffs

For step 2 of the approach, the SD model of the supply chain was used to study high level tradeoffs such as the impact of alternate supply chain configurations. The impact of an alternate off-shore supplier on the energy consumption of the supply chain can be considered with some modifications in the model. In general, one would expect the transport of parts from an off-shore supplier will have a large energy consumption and associated carbon footprint. For example, Nieuwenhuis et al. (2012)

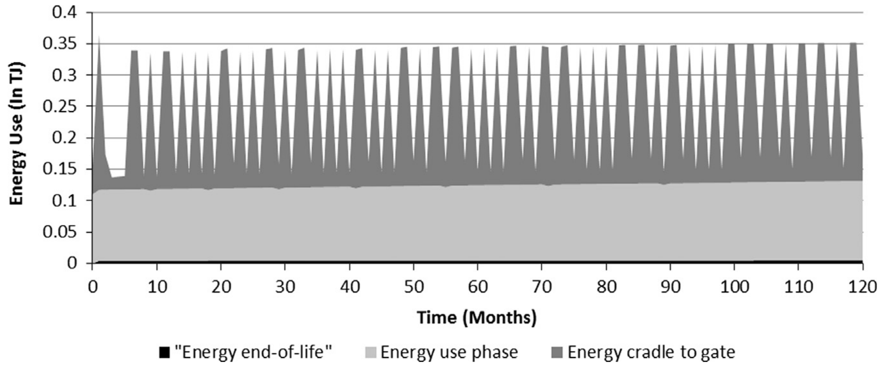

Fig. 4. Stacked graph of energy consumption across the supply chain over ten years with contributions of different phases.

considered the option of off-shore production in automobile industry and found that seaborne sourcing has significantly higher emissions than even a road-based local distribution case. However, the cost of the parts from the off-shore supplier may be lower. An organization has to thus trade-off the relative value they attach to the energy consumption against the monetary cost to decide on the off-shore supplier option. An SD model can help the organization estimate the energy consumption to make this trade-off.

The model can be designed to allow for modeling defined alternate scenarios with only parameter changes. For example, the model has been set-up to allow modeling alternate suppliers through changing the shipping delay parameter that in turn updates the in-transit inventory necessary to maintain continuous supply. Similarly, the distance traveled and the energy consumption per unit distance traveled for the mode (ship for an off-shore supplier) are updated to model the contribution of the logistics link from the offshore supplier.

It is assumed that the off-shore supplier gets the steel from a plant with the same characteristics as the steel plant for the domestic supplier. If the offshore supplier appears to be an attractive option following the initial analysis, information of their raw material sources can be requested and modeled for a more accurate representation. The use of the off-shore supplier for the largest components in the brake system added 104 GJ of energy consumption per year due to transportation over long distance. Fig. 6 shows the comparison of energy consumption of supply chain between the base case with domestic suppliers and the case with offshore suppliers.

The tradeoff facing the brake manufacturer is in terms of cost of the component versus the energy consumption. One possible way to evaluate the tradeoff is to look at the carbon emissions corresponding to the energy consumption and other emissions for the alternate suppliers. Carbon emissions, in turn, can be converted to monetary value using the carbon allowance that is currently estimated at 100 Swedish Kronor/metric ton (Mölndal Energi, 2012), or approximately US$14/metric ton. The cost of additional carbon footprint for the off-shore supplier using carbon allowance amounts to only US$214/year. However, the manufacturer will have to consider the impact of disclosing a larger energy consumption and its corresponding footprint on its current and potential customers to make a decision. The system dynamics model provides the information to better understand the tradeoff and support decision making.

Based on the results of the SD model with alternative configurations, a decision was made to stay with the base case, that is, with the domestic supplier. The decision was in view of the potential impact on the market based on the customer's discomfort with the increased carbon footprint of the offshore supplier alternative. With the configuration selected, we moved to the next step of the approach to identify the candidate nodes for detailed analysis.

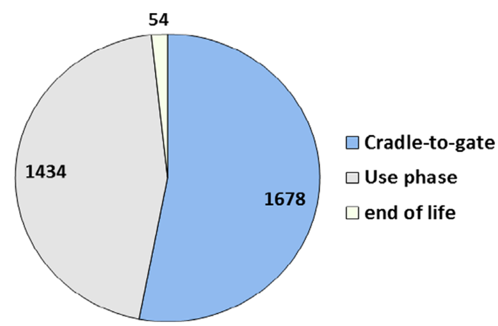

Fig. 5. Contribution of different life cycle phases to the annual energy consumption in Gigajoules (GJ).

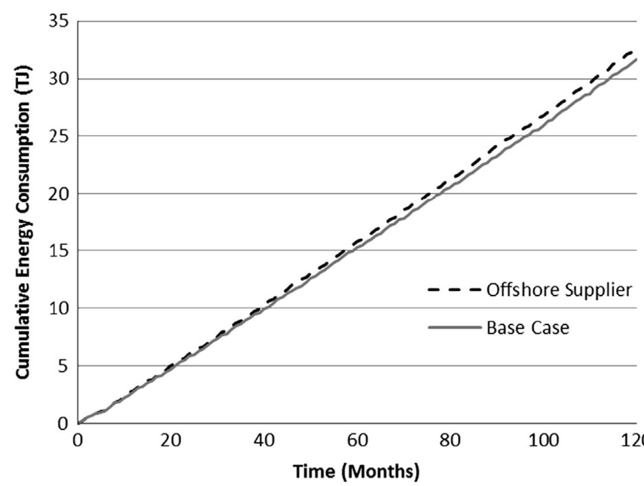

Fig. 6. Comparison of cumulative energy consumption of alternate supply chain configurations using the SD model (in Terajoules (TJ)).

6.5. Potential reductions in energy consumption for the supply chain

The SD model was also used as the vehicle for step 3 of the approach, i.e., for exploring scenarios for potential reduction in energy consumptions at different nodes across the supply chain. It is recommended that a scenario considering all the potential reductions together be used to develop the best case or target for the entire supply chain. Potential reductions were identified for different nodes of the supply chain using the literature as discussed below.

A study by U.S. Department of Energy (U.S. DoE, 2007) estimated that investments in the state-of-art equipment and further research could reduce energy consumption in metal mining by 338.2 TBtu/year out of a consumption of 552.1 TBtu/year, which is a reduction of 61%. This includes 117.5 TBtu/year

(21%) savings from implementing best practices and 220.7 TBtu/year (40%) savings from research and development to improve energy efficiency. The savings estimated in the report are based on a variety of published resources that provided energy efficiencies of top-performing mining equipment. It can be concluded from the overall savings that 21% savings are possible in relatively near term through implementation of existing best practices.

A few efforts have looked at reduction of energy consumption in steel production. Larsson et al. (2006) utilize a process integration model for analyzing the energy consumption in the steel production and pin-point the importance of reducing the energy consumption. They report that several case studies conducted with the method showed a reduction of 4.5 MJ/kg of steel produced out of 18.6 MJ/kg of steel or 24.2% for integrated steel production. Song et al. (2011) report that by using limestone instead of traditional lime into the basic oxygen furnace (BOF) process for slagging it would be possible to save 0.08624 MJ/kg steel produced. Since use of limestone was not a factor considered in the study by Larsson et al. (2006), this potential saving can be added to provide a total potential of saving 4.58624 MJ/kg steel or 24.6%.

The potential for savings at the brake manufacturing node that is primarily a machining and assembly operation was studied by the researchers in the team. Two major factors were identified. A potential savings of 17.6% can be achieved by shutting down the machine overnight and thus save the energy consumed in standby mode. A potential saving of 10% was identified by doing set-ups offline and thus reduce the machine idle times. Thus a total of 27.6% savings in energy consumption is possible at the brake manufacturing operation.

The forklift assembly node can be viewed as a vehicle assembly operation to identify potential energy savings. Price and Ross (1989) indicate that energy savings of 20% are possible in facilities that are like automotive manufacturing. A higher energy saving potential exists during the use phase of forklifts.

Christensen and Patten (2012) estimated 58% reduction in energy consumption of forklifts through improvements in the batteries, chargers, and charging practices.

There are thus a number of potential reductions available across the forklift brake supply chain. The reductions are summarized in Table 3.

The potential reductions in energy consumption were implemented in the SD model to determine the combined impact on the overall supply chain energy consumption. The results of the model indicated a reduction in the overall supply chain annual energy consumption of 29.3%. A comparison of energy consumption for the supply chain under the base case and efficient energy usage scenario cumulated over the 10 year simulated period is shown in Fig. 7.

While the potential reductions were found to be higher at other nodes of the supply chain than brake manufacturing, we will utilize the brake manufacturing node for demonstrating the next step of the approach as we had access to data at the corresponding organization. The potential reductions at the brake manufacturer are further explored using DES model in the next step of the approach. The information on the potential reduction at other nodes can be shared with participating nodes in the supply chain for motivating them to further their energy reduction efforts.

7. Brake manufacturer analysis using DES models

The next step (step 4) in the overall approach is to delve into details for selected parts of the supply chain. The sponsors of this study had control over the brake manufacturing plant and hence that part of the supply chain was selected for detailed study. Data for the simulation model is based on the previous case study in Lindskog et al. (2011) with some adjustments to fit the SD model approach. The brake manufacturing process is shown in Fig. 8, and includes machine processes in-house of raw steel material as well as external machining and a final assembly with components from sub-suppliers. Layout of the brake manufacturing facility is shown in Fig. 9.

7.1. DES model description

The DES model was designed to determine the ecological footprint for each product continuously as it was processed by a resource. The main factor considered was the electricity consumption, which was divided into three parts concerning the consumption during idle and busy state of resources along with an overhead consumption. Analysis was made individually for all resources in the real production facility by power quality monitoring instruments, presented in Table 4, to get valid data of the energy consumption. This approach made it possible to continuously study the energy consumption during the simulation run for each product individually as well as for the total production. Energy consumption that did not derive from machine usage, such as heating and light, were divided among each product as a factory overhead cost. The overhead contribution to the product was calculated from an overhead percentage based on the product's weight comparing with the overall weight for all products.

Input data for other parts of the simulation model was gathered from a variant of sources. The cycle and setup times for each product and machine were collected from the company's enterprise resource planning (ERP) system. The system also provided data about costumer orders, batch sizes, suppliers and material data. For breakdown and repair data time-measurements was used along with complimentary interviews with machine operators. The factory overhead factor data was collected in some parts from the ERP system but mainly from the last two years of invoices.

Table 3
Potential reductions in energy consumption along the supply chain.

Supply chain node	*Potential % reduction in energy consumption*	*Reduction in energy per brake-set produced (MJ)*
Iron ore mine	21%	382
Steel production	24.6%	2461
Brake manufacturing	27.6%	147
Forklift assembly	20%	34
Forklift use	58%	0.24 per forklift hour use

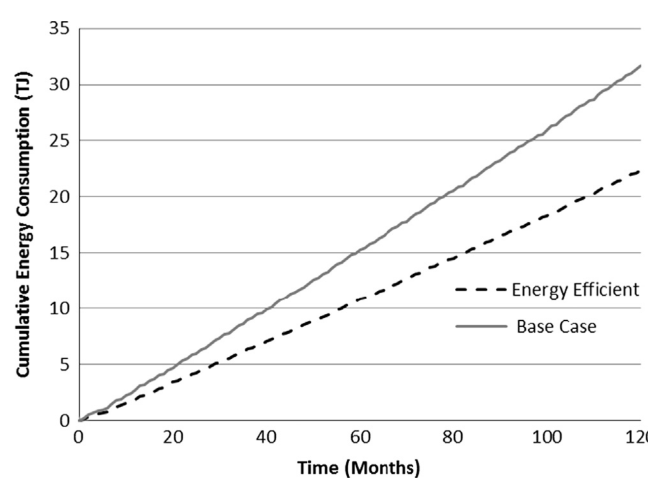

Fig. 7. Comparison of cumulative energy consumption across supply chain life cycle of base case and energy efficient scenarios using the SD model (in TeraJoules).

The result of the simulation was exported to an output spreadsheet after each simulation run to calculate the total energy consumption. Environmental data from LCI databases (such as ELCD, 2011), raw material data, factory overhead costs, and transport distances were included in the output spreadsheet as static values. Verification of the DES model was made continuously by comparing critical processes in the model with the actual production. Simulated production data such as lead times were compared with real production data for validation purposes.

7.2. DES model results

The DES model did show that around 73% of the total energy consumption was contributed from the overhead cost and not directly related to machine processes for manufacturing products. Overhead energy consumption was mainly due to heating up the factory in winter season as well as having unused machines in stand-by mode. The remaining 27% are directly related to machine processes and could be separated into energy consumed in two states: idle and busy. The idle state includes times when the product occupies a machine without processing, for example setup times and material changes. Approximately 30% of the consumed machine energy was a result of the idle state, when machines were not processing components. The result from the simulation model is summarized in Table 5.

It was possible to study each product separately and analyze unstable behaviors in the model that led to variability in the overall production output. Human aspects were shown to be a key part of the unstable result with the variability coming from large proportion of manual work with assembling, welding, setting up machines and internal transports of material. However, human behaviors are quite difficult to simulate, in this case due to lack of standard work methods.

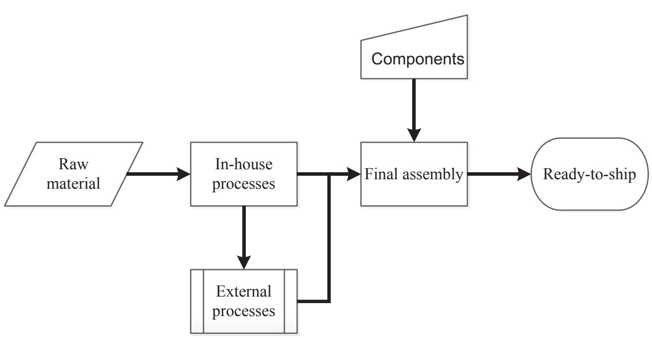

Fig. 8. Flow chart describing the manufacturing process.

7.3. Manufacturing operation tradeoffs

The DES model considered two potential ways to reduce the energy consumption at the brake manufacturer, shutting down machines overnight and reduction of the set-up times. While attractive in concept, it turned out that shutting down machines overnight resulted in additional time in the morning to get the machines started and with the additional time of personnel involved in the process, the expense exceeded the potential savings. This improvement was therefore not recommended for implementation. However, as could be seen in Fig. 10 such an improvement would have a great influence towards the total energy consumption for the brake manufacturing part of the life cycle.

The second means to decrease the amount of consumed energy is to reduce times when products are occupying machines in idle state. Setting up machines for processing new parts was identified as the largest contributor to the idle state time. An overview of the input data shows that the set-up times were on average 29 min with a maximum of 135 min. This in combination with an average energy consumption of 5.18 MJ for machines in idle state results in high energy consumption where the machines could not process any material. By introducing automated set-up of the machines, with predefined programs, it would be possible to reduce all setup times to almost zero. The result of such a simulation is shown in Fig. 10. As could be seen the amount of electricity for idle state is reduced by more than 50% compared with the initial run. The reduction in total energy consumption for one brake-set was found to be 7%. This option was found attractive and recommended for further study and implementation.

Step 4 of the approach thus identified the option for reduction of energy consumption at a particular node in the supply chain and thus in the whole supply chain. Step 5 of the approach was not needed in this case since the operations did not involve interaction with a large number of people external to the organization. Step 6 involved updating the brake manufacturing node data in the SD model. The step is not detailed here as the process is similar to that in step 3.

Overall, the approach thus allowed identification of opportunities for reduction in energy consumption across the supply

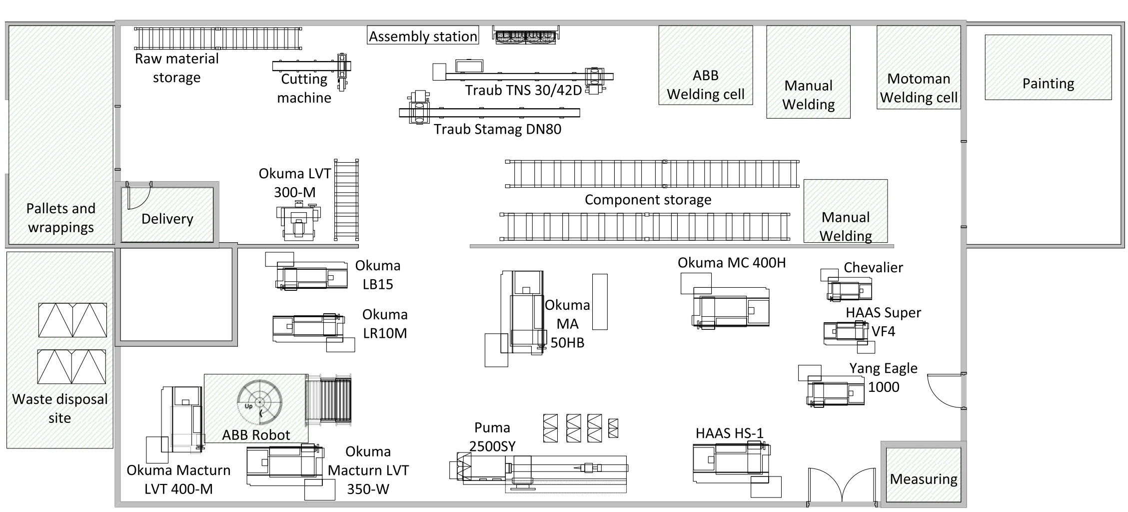

Fig. 9. Layout of the brake manufacturing factory.

Table 4
Energy consumption per process used to manufacturing the brake-set.

Resource type	Resource name	Energy	
		Busy	*Idle*
CNC- and NC-machines	Okuma Macturn LVT 400-M	26.51 MJ	6.32 MJ
	HAAS HS-1	10.32 MJ	3.07 MJ
	Okuma MA 50 HB	16.36 MJ	9.27 MJ
	Okuma MC 400 H	13.57 MJ	9.48 MJ
	Chevalier	5.27 MJ	1.81 MJ
	Okuma LVT 300-M	11.13 MJ	7.09 MJ
	Okuma LR10 M	13.54 MJ	6.66 MJ
	Okuma LB15	13.54 MJ	6.66 MJ
	Yang Eagle 1000	6.42 MJ	2.42 MJ
Manual operations	Manual machine work	1.80 MJ	0.60 MJ
	Manual welding	21.60 MJ	7.19 MJ
	Cutting machine	10.80 MJ	3.60 MJ
	Painting	3.60 MJ	1.20 MJ

Table 5
Results from the DES model (average values based on one year of production).

Product	Energy			Time	
	Busy	*Idle*	*Overhead*	*Lead*	*Process*
Brake-set A	15.21 MJ	10.41 MJ	98.40 MJ	129.27 h	1.31 h
Brake-set B	36.08 MJ	16.74 MJ	110.36 MJ	129.27 h	2.87 h

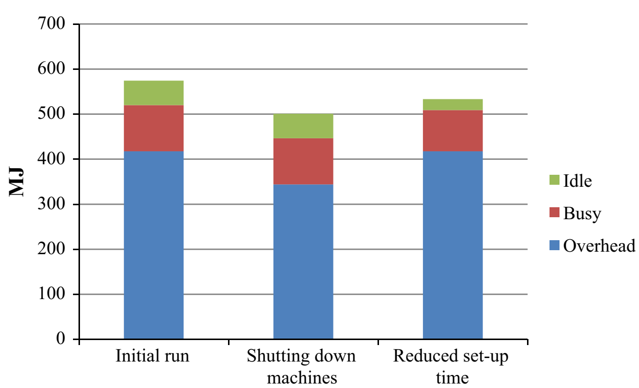

Fig. 10. Energy consumption for manufacturing one brake-set at the brake manufacturing company.

chain. This was achieved through analysis of tradeoffs affecting energy consumption at the high level using SD simulation and at the detailed level using DES. The case study thus demonstrates the usefulness of the approach.

8. Conclusion

This paper presented a hierarchical approach for analysis of tradeoffs in supply chain energy consumption. The approach utilizes SD simulation with a high level representation of the supply chain to assess the energy consumption across the supply chain, evaluate tradeoffs related to supply chain design and operations, and consider the impact of a number of potential ways at different supply chain nodes taken together in reducing the energy consumption across the supply chain. Larger opportunities identified across the supply chain are filtered by the ability to influence the operations of the corresponding node to identify options for detailed study. DES models are used for evaluation of selected opportunities at the detailed level. The opportunities validated through the use of DES can then be presented together with the results to concerned decision makers for consideration for implementation. The validated potential reductions are used to update the higher level model to improve its accuracy and for use in further iterations of the approach to support continuous improvement.

A case study of a closed loop supply chain of a forklift brake system was used to demonstrate the value of the approach. An SD model of the brake system supply chain was used to assess the energy consumption across the supply chain. A number of potential reductions at different nodes were gleaned from the literature and used to identify a target reduction of 29.4% across the supply chain. A scenario of an offshore supplier was evaluated for supply chain design tradeoff using the SD model. A detailed analysis of the brake manufacturer energy consumption was conducted using a DES model. The opportunity of reducing energy consumption through reduction in set-up times was evaluated using DES model. The model mimicked detailed operation of the plant with offline set-up and estimated a 7% reduction in energy consumption.

We plan to extend this work in future by ensuring that the procedures used are in agreement with standard approaches such as those developed by the GHG protocol. We also intend to develop the models further for improved accuracy in estimating energy consumption and emissions. For example, at present the energy consumptions at some of the nodes in the supply chains are projections based on data collected at the brake manufacturing operations. Attempts will be made to improve these estimates through either collection of data at the actual facilities or locating data from representative facilities in the literature. On the modeling side, the SD and DES models will be closely coupled to allow direct communication of information between the two models for issues that require run time interaction. Spreadsheet data interfaces for the two models are also being considered to allow easier maintenance of the models and potential use by industry personnel.

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