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SIMTER – A Joint Simulation Tool for Production Development

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Title

SIMTER
A Joint Simulation Tool for Production Development

Abstract

Digital engineering tools and procedures have had a positive impact on the European manufacturing industry. However, to design a sustainable manufacturing system, a multitude of system dimensions has to be jointly optimized.

Manual work and automation are the complementary elements in the modern production systems. The increasing customization and shortening product lifecycle have led to smaller batch sizes and more varying products. The intelligence and adaptability of human workers make them the most flexible part of the production process. However, production must be optimized with respect to human wellbeing and environmental sustainability.

In the Finnish-Swedish project SIMTER, we developed an integrated simulation tool helping to maximize production efficiency and to balance manual and automated work subject to ergonomics constraints. We examined human factors and environmental impacts as a part of production process optimization. The study based on an extensive literature review and collaboration with the companies, which included interviews, observations and tests with the SIMTER tool.

The project's core result is the SIMTER simulation tool, which enables production simulation jointly taking into account levels of automation, ergonomics, and environmental impacts. The SIMTER tool enables dynamic simulations, instead of static simulations. During the project, we improved a digital human model, which relies on a database of measured and recorded real human motions. In addition, an environmental database was integrated with the simulation tool, so that environmental impact can be assessed while optimizing production. The assessment and choice of different levels of automation create the basis for the production optimization and simulation procedure.

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Preface

The SIMTER project was carried out during 2007–2009 as a result of generous support from eTranet (http://www.etranet.net) funding organised by Finnish and Swedish governmental funding agencies. The project was executed in Finnish-Swedish cooperation. In Finland, the project participants included VTT Technical Research Centre of Finland (project coordinator) and two companies, namely Visual Components and Hollming Works. The Finnish part of the SIMTER project was co-funded by TEKES and VTT. In Sweden, the SIMTER project involved Chalmers University of Technology, Volvo Technology and EKA Chemicals. Swedish funding was provided by VINNOVA, the Swedish Governmental Agency for Innovation Systems.

During the project it became obvious that joint and multi-parameter simulation tools are needed in order to ensure sustainable and effective production. Due to the limited number of available tools and the two-dimensional approach paying attention to human and environment, the SIMTER approach appeared to be an interesting opening. The development work will be continued in the next projects, aiming to improve the analysis methods and usability of SIMTER tool.

Contents

List of symbols

CMSD	Core Manufacturing Simulation Data
DES	Discrete Event Simulation
Eq.	Equivalent
LCA	Life Cycle Analysis
LoA	Level of Automation
MTBF	Mean Time Between Failure
MTTR	Mean Time To Repair
NIST	National Institute of Standards and Technology
SoPI	Square of possible Improvements
UML	Unified Modelling Language

1. Introduction

Simulation is used for problem solving in many real-world cases, providing a safe and cost-efficient environment for difficult decisions. There are numerous different simulation methodologies and software on the market today, all of them with their specific area or branch of applicability. However, each simulation is trying to represent reality only taking heed of the specific parameters evaluated in that specific analysis. This is a problem when the decision makers need to handle a multitude of different parameters, which cannot be incorporated into the analysis of one single simulation. It leads to sub-optimization, when only a few of the many parameters are included in the simulation. Hence, sub-optimization is common when decisions have to be made. The aim of the cross-disciplinary SIMTER project was to improve optimization by introducing and facilitating the use of an increased number of possible parameters, thus enabling joint analysis of multiple and synergistic phenomena.

The SIMTER project considered parameters grouped into three modules – a) ergonomics, b) levels of automation (LoA), and c) environmental impacts – in addition to conventional production simulation parameters. During the project, we described how a few of the parameters normally existing only in separate simulation and analysis tools could be unified to holistically optimize production. The main ingredient in this approach was to produce a tool that would be capable of integrating several aspects of interest for the decision maker, e.g. a production engineer working on either modifying an old or designing a new manufacturing system.

The focus was on production development that is economical, human-centred, and environment-friendly. The identified areas are interdependent and have substantial impact on each other. Therefore, there is a need for conducting analyses accounting for all three viewpoints simultaneously.

1.1 SIMTER core areas

The SIMTER project was grounded on four interrelated areas: discrete event simulation (DES), levels of automation, ergonomics, and environmental impact analysis.

1.1.1 Discrete Event Simulation

Simulation is a powerful problem-solving tool for industry. One of the largest application areas for simulation is manufacturing systems (Law & McComas, 1999). The first uses of this kind of simulation can be traced back to the early 1950's. Since then, the development of the field has been ongoing. However, integration of multidisciplinary parameters and their analyses is a more recent approach (Banks et al., 1996; Law & Kelton, 1999). Simulation analysis provides many production performance indicators. The common aim is to identify problem areas and quantify or optimize production system performance such as throughput under average and peak loads, utilization of resources, labour and machine, staffing requirements, work shifts, bottlenecks, choke points, queuing at work locations, queuing caused by material handling devices and systems, effectiveness of the scheduling system, routing of material, and finally work in process and storage needs. DES constitutes the basis for the SIMTER tool.

1.1.2 Level of Automation

Modern manufacturing systems normally include complex technical equipment as well as skilled human operators. When developing and changing such systems, an important design issue is the allocation of work tasks between humans and automated equipment. Often, such decisions are considered in a more or less binary manner – either a system is automated or it is manual. However, recent research (Fasth, 2009; Frohm, 2008; Harlin et al., 2006) claims that careful consideration and controlled change of the level of automation (LoA), i.e. using gradual increase or decrease of the number of automated tasks, may increase productivity and flexibility in many manufacturing system. Lowering the level of automation in a system may have the downside of increasing operation times. However, the increased number of operations performed manually will have a positive influence on system flexibility and provide for rapid disturbance handling. Experiences from research into operation of computer and aircraft control systems suggest that dynamic but controlled adjustment of the levels of automation in a system may be a powerful tool for semi-automated system control (Frohm, 2008). Parasuraman et al. (2000) also suggested that the level of automation could be assessed and analyzed by decomposing semi-automated tasks into physical and cognitive components. This enables a more detailed design of physical tasks and decision support tools.

The level of automation has natural implications on ergonomic features of a work situation, physical ergonomics as well as cognitive ergonomics. In the SIMTER tool, previously developed tools for level of automation analysis were used and integrated with modules for ergonomics and environmental systems analysis.

1.1.3 Environmental impacts

To be able to consider the environmental impact of a process, it is important that the environmental parameters are assessed simultaneously, in the same simulation model and along with process parameters. Thus, environmental considerations can be made at the time of production planning. However, so far no unified method for this approach has been found.

Life cycle assessment is a method for evaluating environmental impacts associated with a product during its life span (see: EN-ISO 14040:2006; EN-ISO 14044:2006). The assessment can be accomplished by identifying and quantitatively describing the product requirements for energy and materials, the emissions and waste released to the environment. The product under study is examined from the initial extraction and processing of raw materials through manufacturing, distribution, and use, to final disposal, including the transports involved, i.e. its whole life cycle. Typically, industrial modelling with the life cycle assessment describes static models in comparison to DES. Examples of publications from different industrial areas are pharmaceutical intermediates (Jödicke et al., 1999), nitric acid plant (Alexander et al. 2000), boron production (Azapagic & Clift, 1999), phenolic-resin manufacturing (Kheawhon & Hirao, 2004), and cement production (Gäbel & Tillman, 2005). One of the biggest challenges is getting data for environmental impact analysis. The other difficulty is the accuracy or granularity of the models. It has been shown for an automobile machining line that even if the value added process (machining) is not running, the system uses a lot of energy, the maximum energy requirement for the actual machining being only 14.8% of the total. There is a significant energy requirement to start-up and maintain equipment in a “ready” position. Once ready, there follows an additional requirement proportional to the quantity of material being processed (Gutowski et al. 2006). More energy efficient equipment, i.e. variable speed drives and use of frequency converters, normally have a short payback time (Westerkamp 2008). Simulation can help in the evaluation of equipment selection by showing the potential impacts.

In this domain, our intention was to enable life cycle assessment on a detailed level where cause and effect can be measured over time with dynamics from discrete event simulation influencing each product’s way through the production system (“gate to gate”). The SIMTER tool was planned to include Life cycle inventory analysis (LCI) concentrating on the most important environmental aspects of production systems.

1.1.4 Ergonomics

Manual work and automation are complementary elements in modern production systems. The increasing customization and shortening product lifecycle have led to smaller batch sizes and more varying products. The intelligence and adaptability of human workers make them the most flexible part of the production process. In this context, it is desirable to combine human's flexibility with accuracy, speed and force of the machine.

If ergonomics is neglected, industrial working conditions can expose workers to excessive mental and physical stress. Manual work requires the worker to manage different factors simultaneously. Such factors can relate to safety, to the task and to the working environment (see e.g. Helin et al. 2007, Oedewald & Reiman 2007). To harmonize functions and task allocation between the human and the machine, various approaches, such as participatory design, can be applied (Vink et al. 1995, Vink et al. 2006, Rivilis et al. 2008).

In the SIMTER project, we wanted to develop an integrated simulation tool helping to maximize production efficiency and to balance manual and automated work subject to ergonomics constraints. We examined ergonomics and safety as a part of production process optimization. In this process, we employed a digital human model (DHM) "OSKU" (see Helin et al. 2007), which relies on a database of measured and recorded real human motions. A part of this process was improving OSKU and extending it to be a part of production system design. Digital human models have to be implemented in the first case to support engineers in their daily development work (Kaasinen & Norros 2007, Chafin 2007, Nieminen 2004, Määttä 2007, Helin et al. 2007). Furthermore, in analyzing and developing production ergonomics, a number of analysis methods can be applied. Such methods are e.g. task analysis (see e.g., Hackos & Redish, 1998) cognitive work analysis (Vicente, 1999), contextual design (Beyer & Holzblatt, 1999), usability testing (Nielsen, 1993) and heuristic usability evaluations (Nielsen, 1993).

1.1.5 The aims of the SIMTER project

The SIMTER project aimed to produce a simulation tool, which would enable joint multiparameter analysis of a production system. Thus, the project focused on producing three sub-tools (LoA, ergonomics, environmental) and integrating them into a single SIMTER tool. A joint simulation system supports the "Design for All" (DFA) principle that merges usability, accessibility, liberty, and barrier-freeness of environments, products and services to achieve sustainable and robust solutions (Saito 2006).

1.2 Manufacturing System Design

Sustainable manufacturing system design means taking into account both economic and ecological, and social constraints. Sustainable business models and environmental accounting are growing business concerns. However, there are multiple approaches to measuring the total environmental footprint of an organization or supply chain, and as of today there is no agreed-upon single standard. The environmental and climate impacts of energy use are rapidly becoming a major issue facing industry and society. Carbon dioxide (CO_2), a major greenhouse gas, is emitted into the atmosphere directly when fuels are combusted on-site, and indirectly when electricity is consumed (particularly when fossil fuels are used to generate the electricity). The rising cost of energy is also a factor that must be understood during the manufacturing design phase. More energy-efficient solutions can create huge savings during the lifetime of equipment.

A manufacturing system consists of entities (input and outputs), activities, resources and controls (Harrell & Tumay, 1995). It encompasses processes but also includes the resources and controls for carrying them out, as shown in Figure 1.

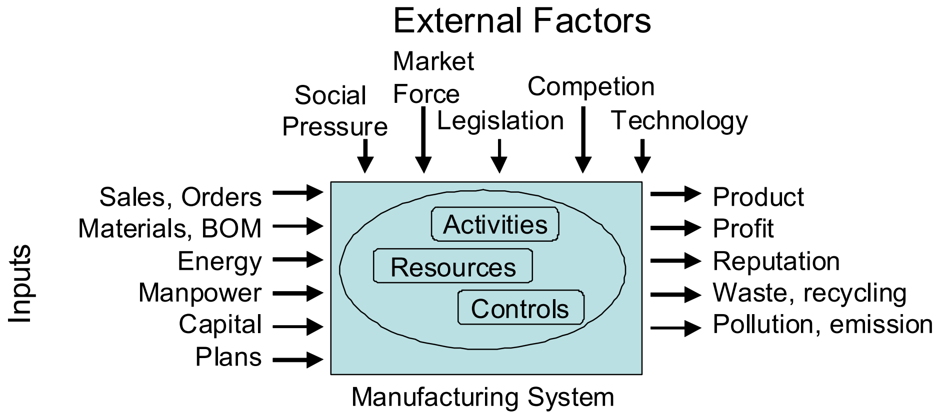

Figure 1. A manufacturing system.

Manufacturing system design involves a number of interrelated subjects including tooling strategy, material-handling systems, system size, process flow configuration, flexibility needed for future engineering changes or capacity adjustment, and space strategy. Production process design is a critical area, since any decision will affect system behaviour for a long time, and/or be very costly to change once the system is up and running. Material handling is another area that deserves intensive study. Although this function does not add value directly to the product, it facilitates the production process flow. System design emphasizes details i.e. how, where, and when the process is to be performed. It selects the right equipment and resources to fulfil the process flow.

Production engineering and management decisions involve the consideration of many interdependent factors and variables as shown here. There are far too many of them for the human mind to cope with at once, in which case simulation modelling could help.

Discrete event/material flow/factory simulation is used in the design phase to evaluate concepts and optimize system solutions before investment decisions are made. The common aim is to identify problem areas, and quantify or optimize production system performance such as throughput under average and peak loads, utilization of resources, labour and machine, staffing requirements, work shifts, bottlenecks, choke points, queuing at work locations, queuing caused by material handling devices and systems, effectiveness of scheduling systems, routing of material, work in process, and storage needs.

1.2.1 Lean Manufacturing

Waste elimination is one of the most effective ways to increase the profitability of any business. Processes either add value or waste during the production of a goods or service. Waste (Japanese *muda*) and its elimination form the core of the Toyota Production System (Monden, 1993), also known as lean manufacturing. Lean typically targets the seven so-called "deadly wastes", which include:

- overproduction
- unnecessary inventory
- excess motion
- waiting
- transportation
- over-processing, inappropriate processing
- non-right the first time, defects.

To eliminate waste, it is important to understand exactly what waste is and where it occurs. While products differ significantly between factories, typical wastes found in manufacturing environments are quite similar. For each kind of waste, there is a strategy to reduce or eliminate its effect on a company, thereby improving overall performance and quality.

When machines are optimally tuned to accomplish the desired work, increased operating efficiency reduces energy waste. TPM (Total Preventative Maintenance), similarly to OEE (Overall Equipment Efficiency) methodology, identifies losses that lower equipment efficiency, e.g. waiting, set-ups, and reduced speed. Emphasis on equipment efficiency can lead to reduced costs, increased productivity, and fewer defects. Eradicating waste and losses in the design phases maximizes the productivity of equipment throughout its lifetime.

DES is one tool for identification of production waste (e.g. waiting, work in process, inventories, transportation). Value Stream Mapping (VSM) and other process modelling methods are also used in lean manufacturing system development and analysis.

Development of a sustainable manufacturing system adds more parameters to be handled simultaneously. This is a problem if the decision-makers need to handle a multitude of different parameters that are not incorporated into the analysis of one single simulation. Normally, simulation tries to represent reality, only paying heed to the specific parameters evaluated in that specific analysis; thus in most cases factory simulation is not used for environmental impact analysis. It leads to sub-optimization, where only a few of the many parameters are included in the simulation.

1.2.2 Environmentally sustainable manufacturing

Sustainable manufacturing must be eco-efficient, and one method used is Life Cycle Assessment (LCA). LCA is a method for evaluating environmental impacts associated with a product during its lifetime (EN-ISO 14040:2006; EN-ISO 14044:2006). The assessment can be accomplished by identifying and quantitatively describing the product requirements for energy and materials, and the emissions and waste released into the environment. The product under study is examined from the initial extraction and processing of raw materials through manufacturing, distribution and use to final disposal, including the transport involved, i.e. its whole life cycle (see Figure 2.)

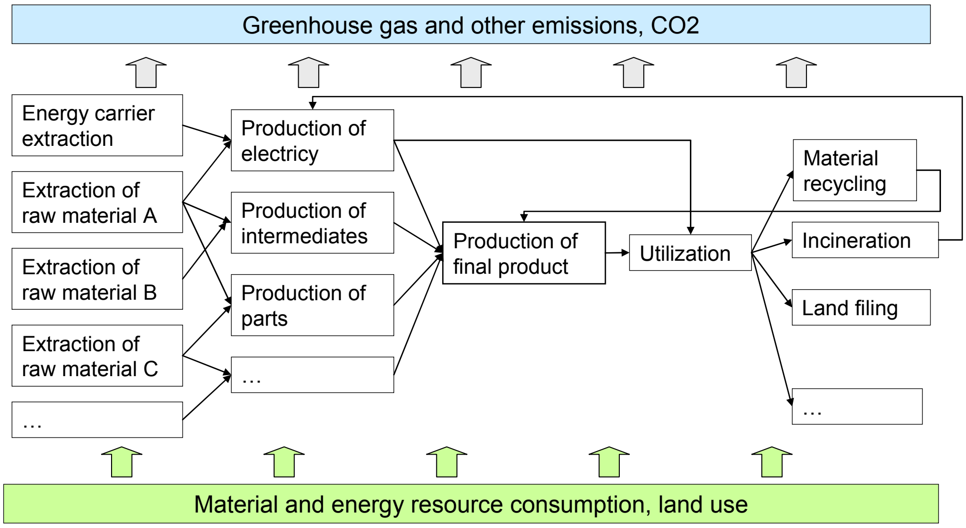

Figure 2. Product life cycle, based on EU LCA platform.

Typically, industrial modelling with LCA describes static models compared to DES. Examples of publications from different industrial areas are pharmaceutical intermediates (Jödicke et al., 1999), a nitric acid plant (Alexander et al., 2000), boron production (Azapagic & Clift, 1999), phenolic-resin manufacturing (Kheawhom & Hirao, 2004), and cement production (Gäbel & Tillman, 2005).

There are some examples of the use of DES: Solding and Thollander (2006) and Solding and Petku (2005) used discrete event simulation to find energy bottlenecks in foundries. Persson and Karlsson (2007), Alvemark and Persson (2007) and Ingvarsson and Johansson (2006) used discrete event simulation as a tool for environmental measurements in food production. A combination of LCA and DES was employed. Five LCA parameters were incorporated in the DES models: CO_2 eq., NO_X eq., SO_2 eq., ethene eq. and energy eq. The results show that it is possible to jointly evaluate economic and environmental impacts.

1.2.2.1 Environmental Waste

According to the U.S. Environmental Protection Agency – EPA[1], environmental waste is an unnecessary use of resources or a substance released into the air, water, or land that could harm human health or the environment. Environmental wastes can occur when companies use resources to provide products or services to customers, and/or when customers use and dispose of products. Environmental wastes include:

1) energy, water, or raw materials consumed in excess of what is needed to meet customer needs
2) pollutants and material wastes released into the environment, such as air emissions, wastewater discharges, hazardous wastes and solid wastes (trash or discarded scrap)
3) hazardous substances that adversely affect human health or the environment during their use in production or their presence in products (EPA, 2007a).

Environmental and energy wastes are not explicitly listed in the "seven deadly wastes" of lean manufacturing, but they are embedded in it and related. Like other lean wastes, environmental wastes do not add customer value. They also represent costs to the enterprise and society in general. Using environmental metrics in lean efforts will allow design engineers and production managers to document the environmental benefits that are part of lean implementation. EPA has assembled a list of environmental metrics that may be of use to organizations implementing lean manufacturing. EPA has also published training material on the Lean and Environment Toolkit (EPA, 2007a) and the Lean and Energy Toolkit (EPA, 2007b).

1.2.2.2 Environmental Metrics

The measures must include priority chemicals that are of particular concern because of their toxicity, persistence in the environment, and/or their potential to bioaccumulate in organisms at higher levels in the food chain. The usage of these chemical and toxic materials should be identified during the production system design.

Companies and other non-governmental organizations have also developed guidance on environmental metrics. The Global Reporting Initiative (2008) provides guidance for company-wide environmental and sustainability metrics. The Facility Reporting Initiative (2008) provides guidance for facility-wide environmental and sustainability metrics. The Greenhouse Gas Protocol Initiative (2008) provides a tool for calculation.

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[1] EPA: http://www.epa.gov

While these resources do not focus explicitly on process level environmental metrics, most of the metrics in these frameworks can be considered and applied at process or sub-process levels.

A more recent approach is GreenSCOR (2008). The SCOR (Supply Chain Operations Reference) model is a proven framework for dealing with supply chain scope and process operations and measuring supply chain performance. SCOR also provides a foundation for environmental accounting in the supply chain. The Supply Chain Council (see: http://www. supply-chain.org) is proposing a set of strategic environmental metrics that can be added to the SCOR model to effectively allow it to be used as a framework for environmental accounting. The proposed metrics are:

- Carbon Emissions, tons CO_2 Equivalent
- Air Pollutant Emissions, tons or kg
- Liquid Waste Generate, tons or kg
- Solid Waste Generate, tons or kg
- % Recycled Waste, percent.

These metrics can be applied in the fabrication phase, at the factory level or even in a single manufacturing phase.

1.2.2.3 EU LCA Platform and other public sources of inventory data

One of the challenges of environmental impact calculation is the data needed. Public sources of information include e.g. the European Commission’s information hub on life cycle thinking-based data, tools and services (see: http://lca.jrc.ec.europa.eu/).

Other public sources of inventory data are as follows: In 1996 the International Iron and Steel Institute (IISI) launched its worldwide life cycle inventory (LCI) study for steel products. The study was updated in 2000 and a second update is due in 2008 (see: http://www.worldsteel.org). An environmental profile report for the European Aluminium Industry is available on the website of the European Aluminium Association (see: http://www.aluminium.org). Eco-profiling and LCA information is provided in Plastics*Europe* (http://www.lca.plasticseurope.org).

Getting detailed data for manufacturing processes like turning, milling or welding is the real challenge, since the parameters depend also on the product.

1.2.3 Ergonomics in manufacturing system design

When designing the production system, the human element becomes the most difficult part to model and simulate due to its inherent uncertainties and variations. Human performance modelling is one key subject in the analysis of level of automation.

Siebers (2004, 2006) presents ideas on how to combine human performance modelling with discrete event simulation. It is important to understand human performance variation. Humans, unlike machines, cannot be modelled with an entirely deterministic logic.

During the production system design process, the required and feasible working postures, working locations, and working manoeuvres should be assessed by simulation or analytically. Besides physical matters, the organisational and cognitive loads have to be taken into account (Vicente 1999, Hollnagel & Woods 1999, Bisantz et al. 2003). The static muscle stress and psychosocial load can be reduced by optimizing biomechanical and mental load, and taking into account workers' feedback (Järvholm et al. 1991, Torner et al. 1991, Westgaard & Winkel 1997, Wilson 1995). Therefore ergonomics should be included in production process and equipment design (Malm et al. 2008, Laine et al. 2007).

In addition to working postures, task design and cognitive matters, also safety should be on of the focal parts in manufacturing system design. Safety and ergonomics can be assessed simultaneously by exploring the latent and active hazards causing direct and indirect exposures (see e.g. Reason 1997). The hazards can be identified with various methods, providing the basis for risk assessment and management. The relevant information can also be utilized in the manufacturing system design, so that the system enables safe and ergonomic task execution.

2. Methods

The state-of-the-art and the requirements for the SIMTER tool were gathered through literature review and interviews at partner companies in Finland and Sweden. The industrial partner companies represented machine building, automotive and chemical industries. The cases for applying the tool were defined within each company. A semi-structured questionnaire was composed to ensure comparable data gathering with interviews. The interviews in companies concerned their production activities, aims and prospects in production development and current problems within the three areas of interest in SIMTER. The findings in companies were used in verifying the final outcome. The actual tool was implemented on the platform of a commercial modular visual discrete event simulation system in the form of software plug-ins. The tool was applied to a company case to test the viability of the concept and the tool.

3. Results

3.1 State-of-the-art review

The body of literature on individual aspects of the theory behind SIMTER is extensive. However, the review revealed that there are only few reported scholar works considering two or more aspects simultaneously.

3.1.1 Ergonomics

Human performance modelling is one key subject in analysis of the level of automation. Siebers (2004, 2006) presents ideas on how to combine human performance modelling with discrete event simulation. It is important to understand human performance variation. Unlike humans, machines can be modelled with a more deterministic logic.

It has been shown that ergonomics and assembly system configurations are closely related in practice. Certain authors (Battini et al., 2007; Salmi et al., 2001) have proposed an integrated, balanced approach for assembly system design and the use of virtual 3D design tool in ergonomic evaluation. The findings in these articles stress the idea that assembly design and ergonomics should be complimentary to each other. One restricting factor is the limited number of suitable commercial simulation tools supporting both assembly system design and ergonomics analysis at the same time.

3.1.2 Levels of Automation

Levels of Automation are often coupled with ergonomics and productivity. Ergonomics improvement may need some automation, for example, in the case of heavy lifting tasks one should automate material handling. There is also a link between ergonomics, productivity and process quality (Battini et al., 2007).

The selection of the most suitable production system is demanding. Productivity and performance issues need to be evaluated during the design and final selection of production system alternatives. Our literature survey indicated that methods based on Overall Equipment Efficiency (OEE), which can be captured in the following three submetrics of equipment or labour efficiency: 1) availability, 2) performance efficiency, and 3) rate of quality (Kronos, 2008). These metrics were used to measure the output of the SIMTER tool simulation and analysis.

3.1.3 Environmental impacts

Solding and Thollander (2006) and Solding and Petku (2005) used discrete event simulation to find environmental bottlenecks affection the environment negatively. A main motivation to do this study was that energy use is the largest cause of environmental problems in the world and foundries use comparatively a lot of energy. Persson and Karlsson (2007), Alvemark and Persson (2007) and Ingvarsson and Johansson 2006), used discrete event simulation as a tool for environmental measurements in food production. A combination of life cycle assessment and discrete event simulation was employed. Five different life cycle assessment parameters were incorporated in the discrete event simulation models, CO_2 eq., NO_X eq., SO_2 eq., ethene eq. and energy eq. The results are very promising for jointly evaluating economy and environmental impact. However, these studies do not include level of automation or ergonomics.

3.2 Technical features and workflow of the SIMTER tool

The SIMTER tool, which can be viewed as an information-processing unit, operates with a number of input and output parameters. At the input, there is a set of alternative manufacturing process layouts having different combination of manual and machine work. The layouts are produced by the designer based on the process requirements, previous generation layouts and standard sub-layouts, known constraints relating to quality, productivity and safety. Each layout has to be supplied with the parameters such as content of tasks (e.g. pick-and-place, fasten etc.), energy and material flows associated with the task as well as other indicators (e.g. failure rates, maintenance costs).

First, the set of alternative process layouts is assessed based on the LoA (see Figure 3). Only the layouts that fit into the LoA "box" (limited by the highest and lowest acceptable LoA values in the dimensions of information and mechanical automation) are retained, hence reducing the search space. Second, for each alternative, the process is simulated to evaluate performance and to highlight the points causing problems in terms of environmental impacts and ergonomics. For complex processes this approach is not feasible due to the dimensionality and the incomplete knowledge of too many process parameters. Therefore, it is better to assess the ergonomics and environmental impacts on the sub-layout level. The ergonomics sub-tool can simulate a sub-layout and to provide the duration and ergonomics scores of a manual task. The environmental sub-tool can perform energy calculations relating to energy consumption (e.g. due to lighting, air-conditioning) and waste (material, energy) of different variations of the same manual or automated task. Third, the process parameters are adjusted and the procedure is iterated (re-simulated) until a satisfactory set of potential solutions is attained.

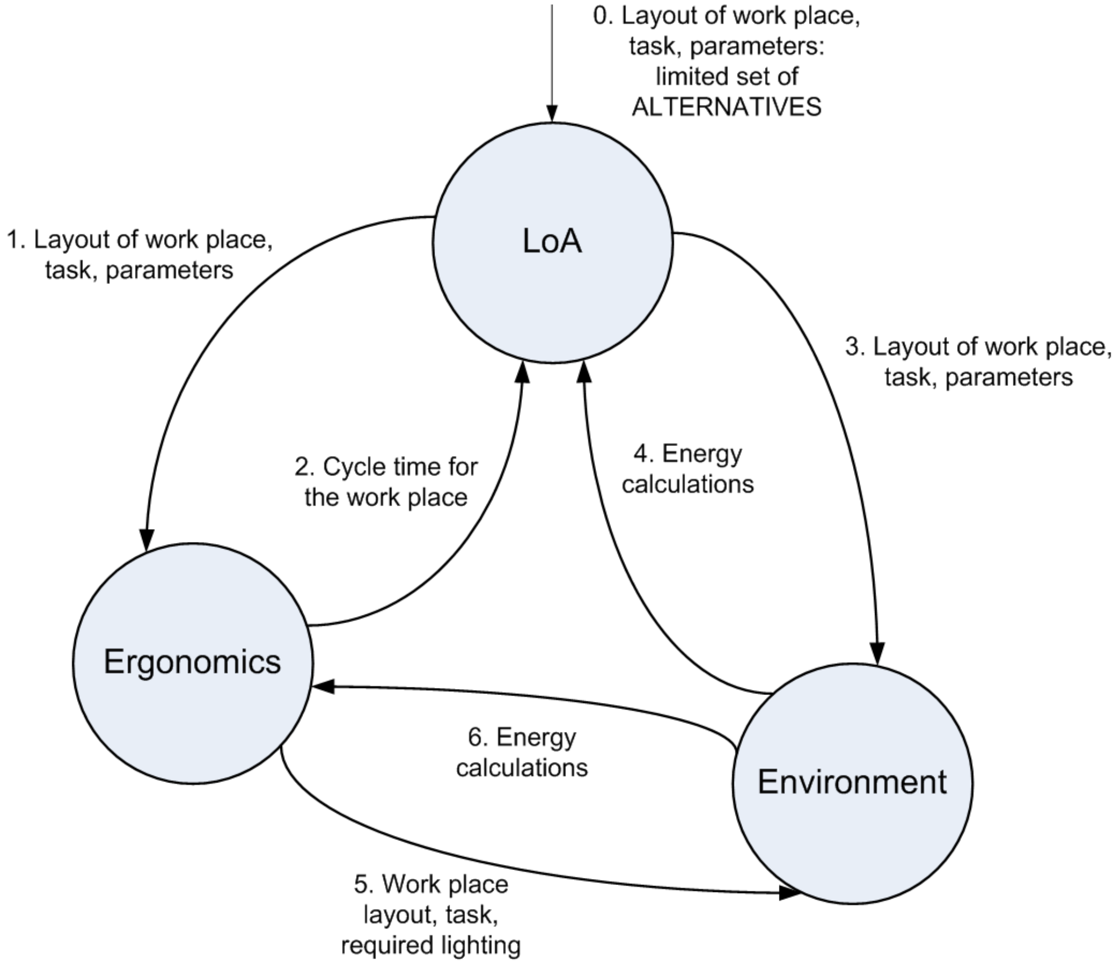


Figure 3. SIMTER tool: Information flow and shared data within the tool.

At the output, the SIMTER tool produces not a point solution, but the factual basis for the decision-making in the form of high-level indicators (e.g. availability, performance efficiency and rate of quality) and guidelines. This is important to ensure that the results are applicable in practice because a point solution is never fully adequate due to inherent process uncertainties and unknown parameters.

The SIMTER tool covers the manufacturing system planning phase (see Figure 4). At the upper level is a discrete event simulation tool analyzing production flow, efficiency and other key performance issues. At the lower, workstation level the focus is on the task, workplace, or process step. Level of Automation (LoA) and ergonomics analysis are also carried out at this level. The lowest level is the product, since material data and part dimensions are needed for analysis.

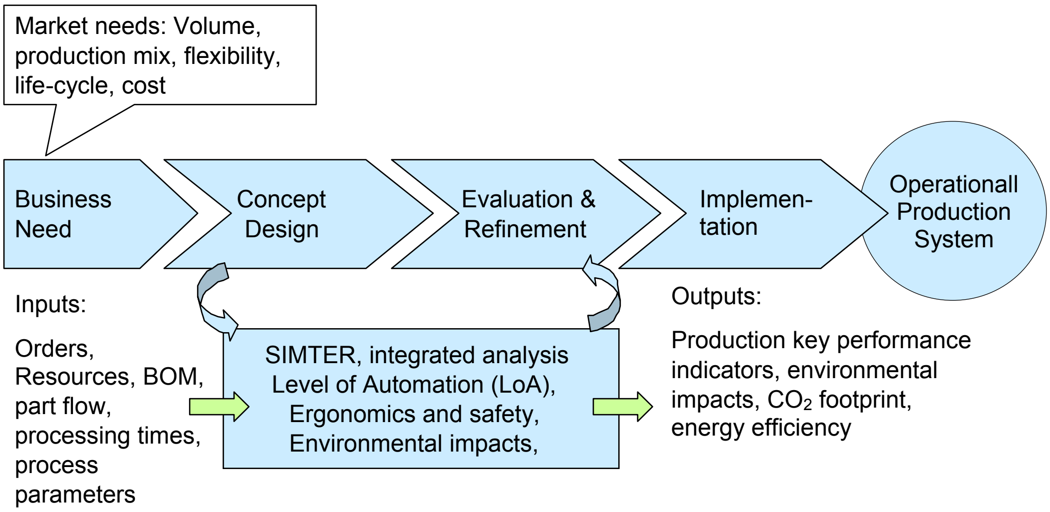


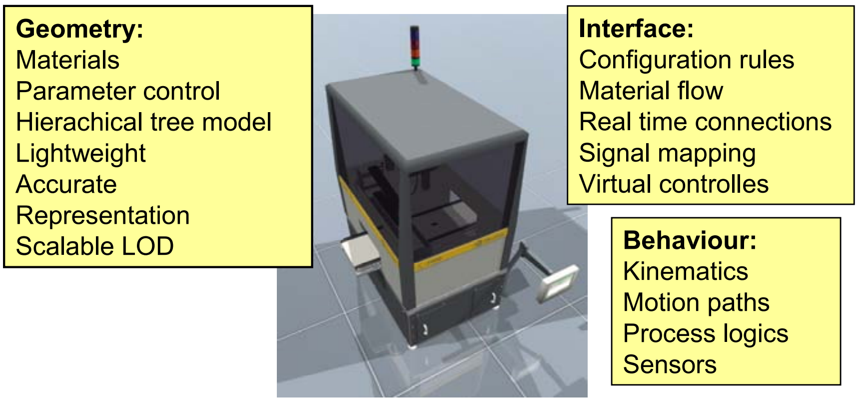
Figure 4. The SIMTER tool covers the system planning phase.

As a conceptual example, consider a task that can be accomplished either by a robot or by a worker. For the robots, the task duration can be obtained using a DES system in combination with the robotics simulation. This functionality is available as a basis of several commercial tools, including Visual Components' *3DCreate* or Dassault Systems' *Igrip*. For the worker, the task duration and ergonomics indexes can be obtained with an ergonomics tool such as OSKU or, in some extent, Dassault Systemes' ergonomics and digital human model functionality. The manual work and the automated work will produce different wastes and will consume energy and materials differently. Hence the environmental analysis will be influenced by the LoA choice. Specific calculations for the environmental impacts can be performed by using the data from existing LCI databases and tools. Here, all three SIMTER sub-areas are interrelated. For instance, choosing a higher automation level may be hindered by the high outage rate or energy consumption. On the other hand, using manual work in a task may be impeded due to its low ergonomics index, excessively high overall process pace or certain chemicals used in the process.

3.3 SIMTER tool

3.3.1 Development platform

In order to avoid using several pieces of simulation software and to reduce the total cost of the SIMTER tool, it has been decided to exploit commercial software that includes both factory and robotic simulation features on a single platform – 3DCreate and 3DRealize of Visual Components (see: http://www.visualcomponents.com). If pre-engineered re-usable sub-model elements are available, model building is a rapid process (see Figure 5a & 5b). 3D features are needed in ergonomic analysis with a digital human model or robotic work-cell design.



Geometry:
Materials
Parameter control
Hierachical tree model
Lightweight
Accurate
Representation
Scalable LOD

Interface:
Configuration rules
Material flow
Real time connections
Signal mapping
Virtual controlles

Behaviour:
Kinematics
Motion paths
Process logics
Sensors

Figure 5a. Digital Component properties.

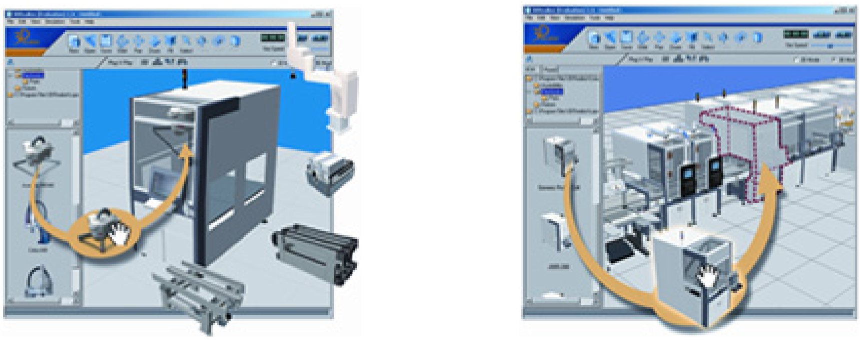


Figure 5b. Component based simulation.

The selected system is extendable and supports add-on application development. Two examples reported earlier are: 1) the OSKU digital man model (Helin et al. 2007) which, in fact, is expected to be developed further in the SIMTER project, and 2) Total Cost of Ownership (TCO) (Heilala et al. 2006 and 2007) analysis methodology integration. It is possible to integrate the external application into the simulation, and to read and write data from/to spreadsheets or other external files.

The selected component-based simulation software with 3D capabilities is needed for fast design and system analysis. Pre-engineered re-usable sub-model elements are available; new can also be created if needed. The advantage of using 3D simulation is visualization of the system, which improves communication. 3D features are also needed in ergonomic analysis or robotic work-cell design. Finally, selected system is extendable and support add-on application development. It is also possible to integrate external application to simulation, to read and to write data from/to spreadsheets or other external files. In the SIMTER tool the three SIMTER sub-areas: ergonomics, LoA, and environmental impacts, are implemented as plug-ins on the 3DCreate platform.

3.3.2 Ergonomics Subtool

Several common and validated methods for evaluating the ergonomics of working postures are employed in the SIMTER tool. Such methods include RULA (McAtamney & Corlett, 1993), OWAS (Karhu et al., 1977), and ERGOKAN (Määttä, 1994). RULA (Rapid Upper Limb Assessment) is a survey method for investigating biomechanical and postural loading on the upper body, with particular attention to neck, trunk and upper limbs. OWAS (Ovako Working Posture Analysing System) identifies and evaluates potentially harmful working postures using a scoring system. It can reveal the frequency and relative proportion of time spent in potentially harmful postures. Finally, ERGOKAN combines RULA and OWAS.

In analyzing and developing production ergonomics, a number of analysis methods can be applied. Such methods are, for example, task analysis (Määttä 1994), cognitive work analysis (Vicente 1999), contextual design (Beyer & Holzblatt 1999), usability testing (Nielsen 1993), heuristic usability evaluations (Nielsen 1993), ergonomics analyses (Karhu et al. 1977), and participatory design (Muller & Kuhn 1993). In the SIMTER tool, cognitive ergonomics could be included using e.g. task analysis, link analysis, check lists, questionnaires or visual/aural simulations (Hollnagel & Woods 1999, Vicente 1999, Stanton 2006).

The development process of OSKU proceeded in the following directions. The improvement was achieved by applying neural networks for filtering raw data, motion spatial and temporal non-linear interpolation, and statistical interval estimation of motion trajectory and duration. The measurements were conducted using motion tracking system, where the sensors were attached to hands, head and the sitting point. The recorded movements included upper limb tracks from the sitting and standing positions. The motion data was utilized to train and validate the neural network. The purpose of the network was to predict humanlike motions for arbitrary starting and ending points without relying on a fixed-grid motion database. Utilising the new motion prediction extends the simulation modelling capabilities of the OSKU tool by extending the motion prediction accuracy and giving freedom to model all task-related motions in a realistic way. Moreover, the posture, link and task analyses will be calculated according to these motions.

The hardware and software for data collection was improved by employing Virtools software (see: http://www.virtools.com/) allowing flexible data collection in a variety of usage scenarios: pick-and-place, welding, light assembly and office work. For the measurements, we designed a data glove to increase the precision of motion duration measurements and to automate the data collection process. Thus, the subject can perform measurements without an assistant. As the motion tracking system bases on magnetic field, the measurements were carried using all wooden custom-made furniture to prevent electromagnetic interference.

The network was prototyped in Matlab (http://www.mathworks.com) neural network toolbox and it is now complete to process 3D data for six sensors (filtering and interpolating in 18 dimensions). The data collection for the network training and validation is being carried out. The parameters of the trained and validated network will be used on Visual Components platform, merging motion visualization, production simulation and ergonomics analyses. An example of motions predicted with the network is shown in Figure 6.

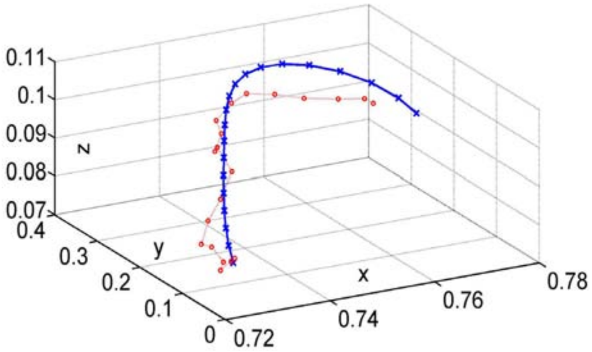


Figure 6. An example of motion prediction.

The dotted line represents the noisy validation data, whereas the solid line indicates the predicted interpolated motion. The discrepancy between the two is about 1–2 centimetres, which is even more precise than the motion tracking system's precision (5–7 centimetres) due to averaging over an ensemble of trajectories. As a result from improvements in OSKU, the ergonomics sub-tool enables accurate simulation (interval estimates) of human motions and the cycle times in a preferred set of tasks for which the network is trained.

3.3.3 The Level of Automation Subtool

The Level of Automation Subtool enables the system designer to use Level of Automation as a design parameter when designing or redesigning a manufacturing system. Figure 3 describes the connections in-between level of automation choices and environmental impact/ergonomics. There is a trade-off which will enable the system to perform differently depending on which configuration is chosen.

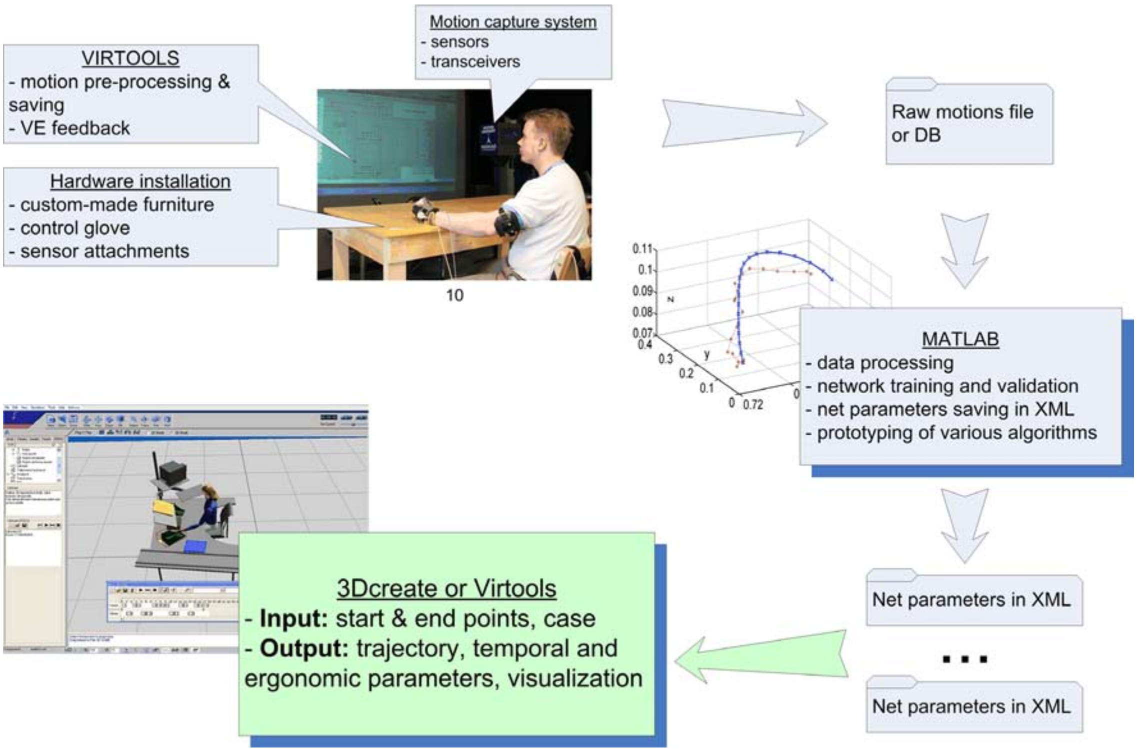


Figure 7. Overview of the data collection and tuning process for the Ergonomics subtool. The data collection and tuning are preformed off-line and then the network parameters are imported to the target virtual environment software (3D Create or Virtools) and used on-line for trajectory prediction.

3.3.3.1 LoA as a design parameter

The concept Levels of Automation (LoA) used here has been defined by Frohm (Frohm, 2008) as “the allocation of physical and cognitive tasks between humans and technology, described as a continuum ranging from totally manual to totally automatic”. The physical activities means the level of automation of mechanical activities, mechanical LoA while the level of cognitive activities is called information LoA. Table 1 shows the reference scale for different Levels of Automation. The LoA levels, mechanical or information, can be interpleaded, thus it creates a matrix 7x7, with 49 possible combinations. The 49 possible solutions are then limited to a relative max and min level for the different scales and creates a SoPI (Square of Possible Solutions) based on the company’s goal function, ergonomic and environmental issues, investment cost etc (Fasth et al., 2008). These possible solutions are then used as an input in the SIMTER tool.

3. Results

Table 1. Level of Automation (LoA) scales for mechanised and computerised task (Frohm, 2008).

LoA	Mechanical and Equipment Level of Automation (Mechanical LoA)	Information and Control Level of Automation (Information LoA)
1	**Totally manual** – Totally manual work, no tools are used, only the user's own muscle power. E.g. the user's own muscle power.	**Totally manual** – The user creates his/her own understanding of the situation and develops his/her course of action based on his/her earlier experience and knowledge. E.g. the user's earlier experience and knowledge.
2	**Static hand tool** – Manual work with support of a static tool. E.g. screwdriver.	**Decision giving** – The user gets information about what to do or a proposal for how the task can be achieved. E.g. work order.
3	**Flexible hand tool** – Manual work with the support of a flexible tool. E.g. adjustable spanner.	**Teaching –** The user gets instruction about how the task can be achieved. E.g. checklists, manuals.
4	**Automated hand tool** – Manual work with the support of an automated tool. E.g. hydraulic bolt driver.	**Questioning** – The technology questions the execution, if the execution deviates from what the technology considers suitable. E.g. verification before action.
5	**Static machine/workstation** – Automatic work by a machine that is designed for a specific task. E.g. lathe.	**Supervision** – The technology calls for the users' attention, and directs it to the present task. E.g. alarms.
6	Flexible machine/workstation – Automatic work by a machine that can be reconfigured for different tasks. E.g. CNC machine.	**Intervene** – The technology takes over and corrects the action, if the executions deviate from what the technology considers suitable. E.g. thermostat.
7	**Totally automatic** – Totally automatic work. The machine solves all deviations or problems that occur by itself. E.g. autonomous systems.	**Totally automatic** – All information and control are handled by the technology. The user is never involved. E.g. autonomous systems.

A manufacturing system is an integrated combination of processes, machine systems, people, organisational structures, information flows, control systems and computers whose purpose is to achieve economic product manufacture and internationally competitive performance. Automation, selection of level of automation, is usually a strategic decision depending on many variables, starting from the product itself. Some product might be out of reach of human operator, due size, process or quality reason. The other common parameters here are; process technology related, flexibility need, type of equipment and technology level available and system layout. Some others are facilities related, location, country, factory size as well the planned capacity. Groover (2001) lists a number of reasons for automation:

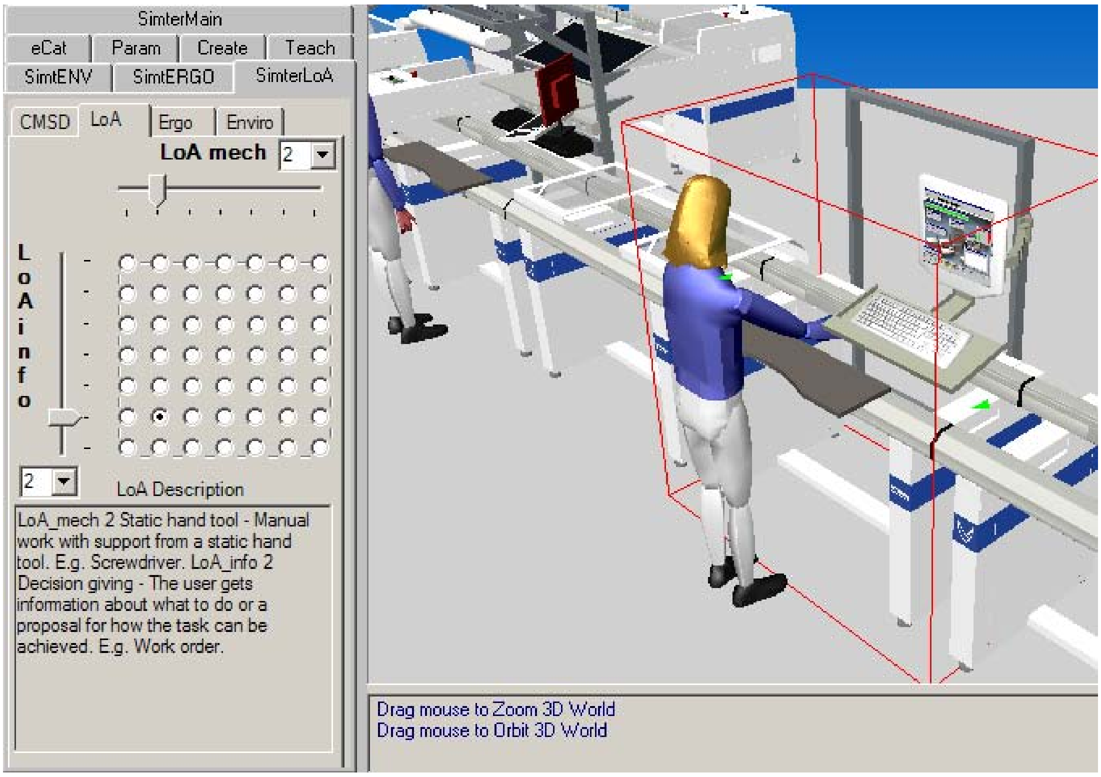
1. to increase labour productivity
2. to reduce labour cost

3. to mitigate the effects of labour shortages
4. to reduce or eliminate routine manual and clerical tasks
5. to improve worker safety
6. to improve product quality
7. to reduce manufacturing lead time
8. to accomplish processes that cannot be done manually
9. to avoid the high cost of not automating.

Some of these may be considered top-down reasons, i.e. they are ‘forced’ on the operations level from top management and some others are more likely to emanate from bottom-up, i.e. they are initiated by other than business related reasons. Engineer and managers need to justify the decisions on automation or not to automate. Findings from (Fasth & Stahre, 2008) show that a majority of the companies that has been analysed needs to change their cognitive automation level and improve the production logistics before changing the mechanical LoA. To be able to distinguish the most advantageous cognitive and mechanical for a specific task or operation, a method called DYNAMO++ has been developed so companies can analyse the current and the future system in a structured way (Fasth & Stahre, 2008: Fasth et al. 2008).

Discrete event simulation is a suitable tool for the analysis of effects and thus supports effective decision-making. The normal performance indicators; cost, quality, time are always present. Appropriate level of automation is expected to have positive effects on the manufacturing performance. LoA has an impact to operating cost (labour, other variable cost) as well to fixed cost, investment to equipments and automation and all the cost related to the planned life cycle of the equipment should be analysed. Total cost of ownership analysis integrated to simulation studies is shown by Heilala et al. (2006, 2007). The cost calculations done in the SIMTER tools does as of now not include monetary units, however a cost index can be used in comparison with investments for machines and labour costs over time in order to compare with environmental impact and ergonomics.

Figure 8 shows an example where the Level of Automation is set to LoA mechanical 2 and LoA information 2.



LoA mech 2

LoA info 2

LoA_mech 2 Static hand tool - Manual work with support from a static hand tool. E.g. Screwdriver. LoA_info 2 Decision giving - The user gets information about what to do or a proposal for how the task can be achieved. E.g. Work order.

Drag mouse to Zoom 3D World
Drag mouse to Orbit 3D World

Figure 8. Part of the system design interface where LoA can be altered. This setting shows LoA Mech 2 and LoA Info 2.

The subtool is based upon a draft standard on how to describe a manufacturing system. The standard effort is entitled Core Manufacturing Simulation Data (CMSD) (SISO, 2009) which can be seen in the top left part in Figure 8 as well.

3.3.3.2 Core Manufacturing Simulation Data

Information management problems affect many aspects of manufacturing operations. They are a particular hindrance to the development and reuse of manufacturing simulations. To facilitate a data driven approach and to enable an automated input data management for simulation models, a standardized format for presenting the data to the simulation models is strongly desirable. Without a standardized data format, the interface between different data sources and storage systems and the simulation model will have to be customized each time a new application is introduced. An effort is underway by researchers from the National Institute of Standards and Technology (NIST) and Chalmers University of Technology, in collaboration with industrial partners, on a standard development effort CMSD (SISO, 2009).

The CMSD specification describes a CMSD information model using the Unified Modelling Language (UML, 2009). The primary objective of this information model is to provide a data specification for efficient exchange of manufacturing life-cycle data in a simulation environment. Objectives of the CMSD effort are to:

- foster the development and use of simulations in manufacturing operations
- facilitate data exchange between simulation and other manufacturing software applications
- enable and facilitate better testing and evaluation of manufacturing software
- increase manufacturing application interoperability.

The CMSD information model addresses issues related to information management and manufacturing simulation development and provides means to define information about many kinds of manufacturing objects. It facilitates the exchange of information between manufacturing-oriented simulations and other applications in the manufacturing domains, such as process planning, scheduling, inventory management, production management, and plant layout. The information model is not intended to be an all-inclusive definition of either the entire manufacturing domain or simulation domain. The model describes the essential or core entities in the manufacturing domain and the relationships between those entities needed to create manufacturing-oriented simulations.

For the CMSD information model to work properly in a real life industrial operation environment, some data treatment will be needed from each of the IT-systems involved, in order to achieve the data in an interoperable format such as CMSD. In the case of the SIMTER tool presented in this report, the CMSD data structure is enabled in Visual Components' 3DCreate fro the first time. It handles resource data for all resources in the model, it handles cycletimes for all operations, as well as disturbances in the format:

- Mean Time Between Failure (MTBF)
- Mean Time To Repair (MTTR).

The CMSD standard format is available for all 7x7 (49) possible automation levels, CMSD data can be both loaded to a resource/model and saved for all resources from a model.

3.3.4 SIMTER Environmental Subtool

The environmental sub-tool enables environmental impact analysis integrated into DES modelling. The integration is a hybrid method, a combination of DES and analytic calculation (Figure 9). Traditional factory simulation, DES run results are used for analytical calculation of environmental metrics.

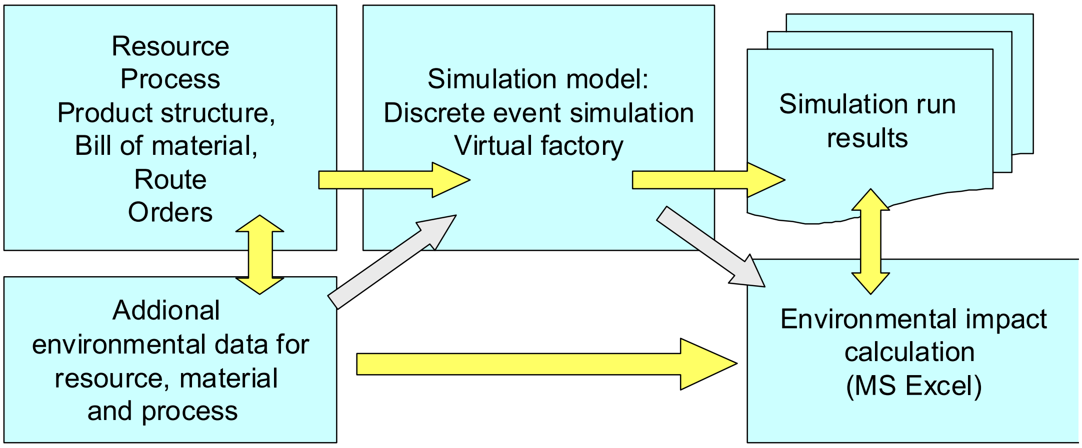


Figure 9. Simplified analysis flow.

To be able to consider the environmental impacts of a process, it is important that the environmental parameters are assessed simultaneously in the same simulation model along with the process parameters. Thus, the environmental considerations can be made at the time of production system planning. However, so far no unified method for this approach has been found. In this domain, the intent of the SIMTER tool is to enable Life Cycle Assessment on a detailed level, where cause and effect can be measured over time with the dynamics of discrete event simulation influencing each product's way through the production system ("gate to gate"). The SIMTER tool includes Life Cycle Inventory Analysis (LCI) concentrating on the most important environmental aspects of production systems.

Discrete event simulation needs resource, bill of material and product route data, process, order, production schedule, volume, mix, and data for system availability, set-ups, planned maintenance, reliability, machine breaks and production quality rate data. As output we get equipment operation data; percentages of machine states (on, off, standby, under repair), thus getting the basis for energy need calculations. From capacity data we are able to calculate factors depending on piece count and material used during operations.

3.3.4.1 SIMTER Environmental metrics

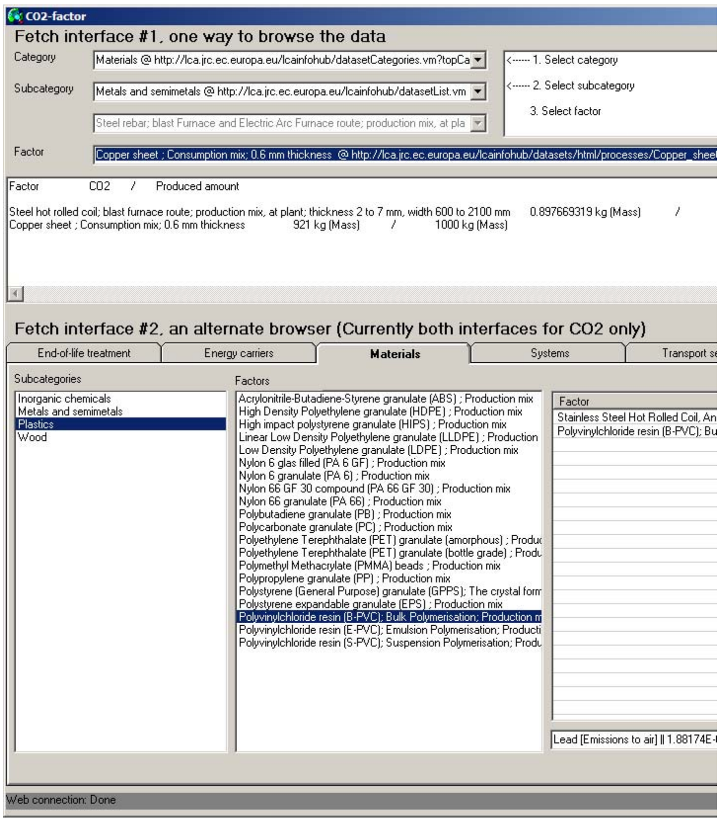
The environmental metrics were adapted from EPA and GreenSCOR. During the development the following metrics were tested:

- energy consumption, direct and indirect
- CO_2 emissions, direct and indirect
- other air emissions NOx, VOC, etc.
- solid waste, hazardous waste
- water emissions.

Environmental calculations are based on the number of products manufactured, raw materials used, machine utilizations, scrap and rework rate. The results of production simulation runs used in analysis are based on the time-unit (i.e. machine operation time), number of working cycles done, or number of manufactured units. For example, electricity usage, cost of energy and also indirect CO_2 emissions from a machine are based on equipment operating data. If there are any process phases or equipment consuming fuels, the direct CO_2 is also calculated.

3.3.4.2 LCI data

Part of the development was to get environmental inventory data as easily as possible and preferably using public databases. One example is shown in Figure 10. In the development phase, various methods for data browsing were tested.



Category: Materials @ http://lca.jrc.ec.europa.eu/lcainfohub/datasetCategories.vm?topCa

Subcategory: Metals and semimetals @ http://lca.jrc.ec.europa.eu/lcainfohub/datasetList.vm

Steel rebar; blast Furnace and Electric Arc Furnace route; production mix, at pla

Factor: Copper sheet ; Consumption mix; 0.6 mm thickness @ http://lca.jrc.ec.europa.eu/lcainfohub/datasets/html/processes/Copper_sheet

```
Factor          CO2    /     Produced amount

Steel hot rolled coil; blast furnace route; production mix, at plant; thickness 2 to 7 mm, width 600 to 2100 mm     0.897669319 kg (Mass)        /
Copper sheet ; Consumption mix; 0.6 mm thickness          921 kg (Mass)       /          1000 kg (Mass)
```

Subcategories:
- Inorganic chemicals
- Metals and semimetals
- Plastics
- Wood

Factors:
- Acrylonitrile-Butadiene-Styrene granulate (ABS) ; Production mix
- High Density Polyethylene granulate (HDPE) ; Production mix
- High impact polystyrene granulate (HIPS) ; Production mix
- Linear Low Density Polyethylene granulate (LLDPE) ; Production
- Low Density Polyethylene granulate (LDPE) ; Production mix
- Nylon 6 glas filled (PA 6 GF) ; Production mix
- Nylon 6 granulate (PA 6) ; Production mix
- Nylon 66 GF 30 compound (PA 66 GF 30) ; Production mix
- Nylon 66 granulate (PA 66) ; Production mix
- Polybutadiene granulate (PB) ; Production mix
- Polycarbonate granulate (PC) ; Production mix
- Polyethylene Terephthalate (PET) granulate (amorphous) ; Produc
- Polyethylene Terephthalate (PET) granulate (bottle grade) ; Produ
- Polymethyl Methacrylate (PMMA) beads ; Production mix
- Polypropylene granulate (PP) ; Production mix
- Polystyrene (General Purpose) granulate (GPPS); The crystal form
- Polystyrene expandable granulate (EPS) ; Production mix
- Polyvinylchloride resin (B-PVC); Bulk Polymerisation; Production m
- Polyvinylchloride resin (E-PVC); Emulsion Polymerisation; Producti
- Polyvinylchloride resin (S-PVC); Suspension Polymerisation; Produ

Factor:
- Stainless Steel Hot Rolled Coil, An
- Polyvinylchloride resin (B-PVC); Bu

Lead [Emissions to air] || 1.88174E-

Web connection: Done

Figure 10. Retrieving data from the EU’s LCA platform.

Based on various partially commercial databases, both material related data and manufacturing process data are available. The data is entered by the user into the SIMTER input database. In the analysis phase, the environmental data and simulation run results are combined in an MS Excel workbook.

3.3.4.3 Energy efficiency analysis

The SIMTER technique estimates energy use based on information provided by equipment manufacturers. It calculates energy use for specific equipment or process activities using equipment energy specifications (often obtained from equipment manuals or vendors) coupled with equipment operation data (e.g. number of hours the equipment is in different modes of operation). While such calculations are not very precise, they can indicate the order of magnitude of energy use. This type of analysis can look not only at where and how much energy is used, but also opportunities to reduce energy costs through load shifting (shifting electricity use to off-peak times), changing the mix of energy sources, and other strategies as well.

Peak rate energy is more expensive. One of the primary data sources for energy cost data is the facility's utility bill (EPA 2007b). Utility bills often include the following types of data: 1) Consumption charges; electricity is charged based, in part, on the amount of electricity used (in kilowatt-hours, kWh) over a billing period. The per kilowatt-hour rate for electricity may vary based on the time of year (e.g. winter or summer season) and/or the time of day (peak or off-peak hours). 2) Demand charges; for many industrial electricity customers, there will be a demand charge (per kilowatt) in the bill that is based on the peak electricity use each month averaged over a short time period (e.g. 15 minutes). The facility may pay more for demand costs than consumption costs, although the two costs may be a single line item in the utility bill. Thus we need to show and calculate peak demands of energy. By lowering or shifting peak demand, the cost can be reduced. Potential energy saving could be 20–27 % or even more (EPA 2007b, Westerkamp 2008). The energy is also the biggest factor in terms of CO_2 emissions at the discrete manufacturing factory level. Longer supply chain also increases emissions during transportation.

3.3.5 Illustrative Case Example

The following illustrative case simulation model was built using existing simulation model library components. The SIMTER "Toy Case" has 5 processing steps, assembly (automated and manual workstation), inspection, painting, drying and packing, as shown in Figures 11 and 12.

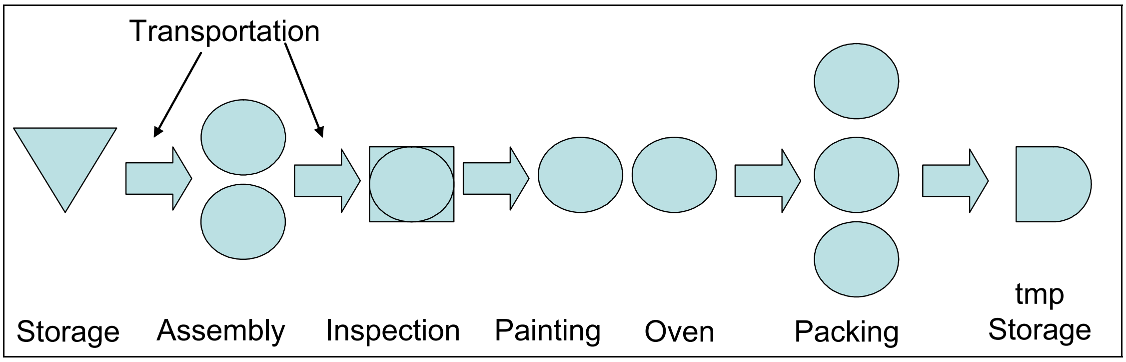


Figure 11. Process flow of case example.

The product consists of four parts, made from electronics plastics, wood and iron. The simulation model shown in Figure 11 might be infeasible in real life, but was a good case for testing the method.

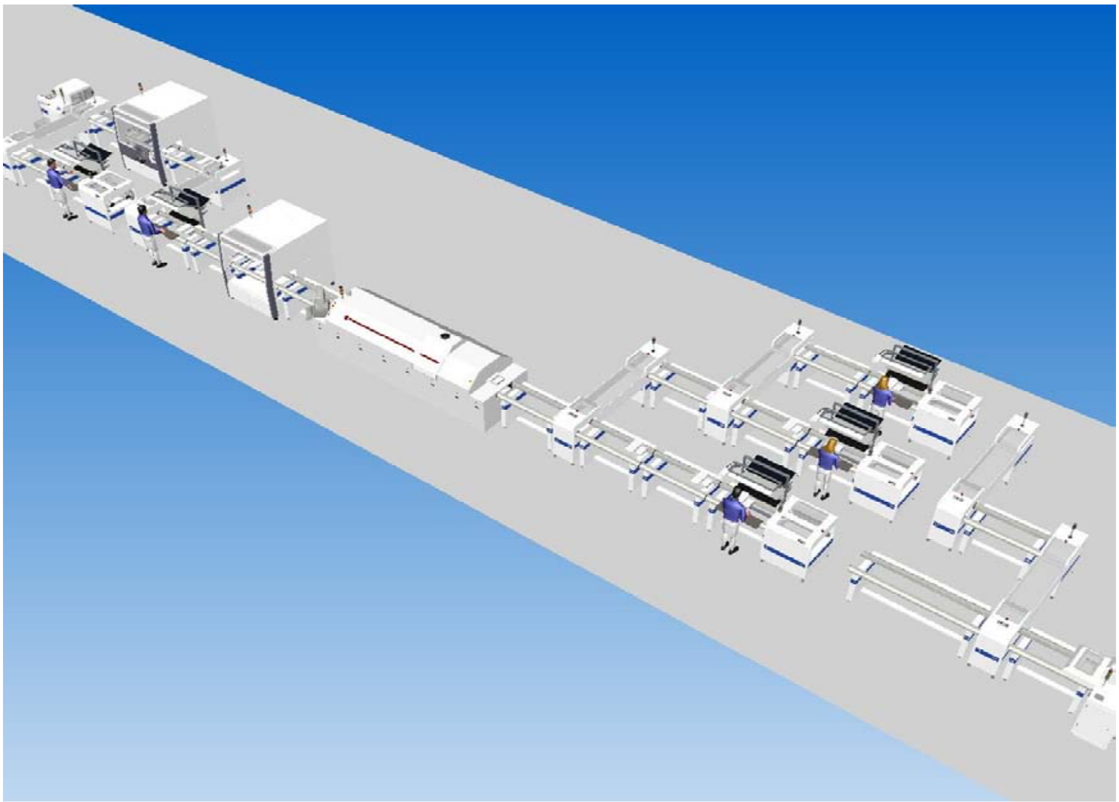
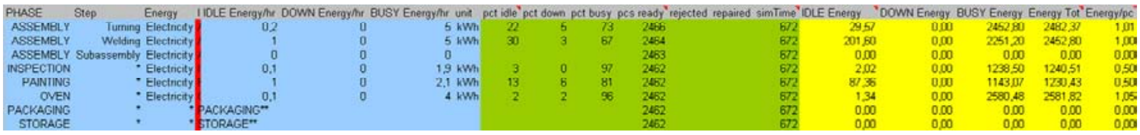


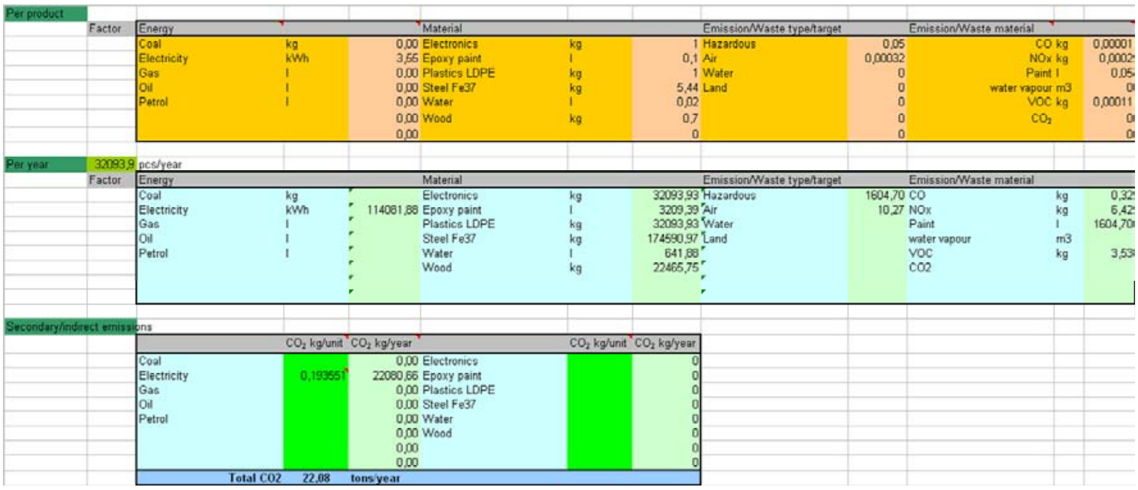
Figure 12. Simulation model.

At the current development state, environmental impact is calculated in an MS Excel workbook as shown in Figures 13 and 14. The simulation model can read and write data from/onto an Excel sheet.



PHASE	Step	Energy	I IDLE Energy/hr	DOWN Energy/hr	BUSY Energy/hr	unit	pct idle	pct down	pct busy	pcs ready	rejected	repaired	simTime	IDLE Energy	DOWN Energy	BUSY Energy	Energy Tot	Energy/pc
ASSEMBLY	Turning	Electricity	0,2	0	5	kWh	22	5	73	2466			672	29,57	0,00	2452,80	2482,37	1,01
ASSEMBLY	Welding	Electricity	1	0	5	kWh	30	3	67	2464			672	201,60	0,00	2251,20	2452,80	1,00
ASSEMBLY	Subassembly	Electricity	0	0	0					2463			672	0,00	0,00	0,00	0,00	0,00
INSPECTION	*	Electricity	0,1	0	1,9	kWh	3	0	97	2462			672	2,02	0,00	1238,50	1240,51	0,50
PAINTING	*	Electricity	1	0	2,1	kWh	13	6	81	2462			672	87,36	0,00	1143,07	1230,43	0,50
OVEN	*	Electricity	0,1	0	4	kWh	2	2	96	2462			672	1,34	0,00	2580,48	2581,82	1,05
PACKAGING	*	*	PACKAGING**							2462			672	0,00	0,00	0,00	0,00	0,00
STORAGE	*	*	STORAGE**							2462			672	0,00	0,00	0,00	0,00	0,00

Figure 13. Resource sheet: equipment energy data, simulation run results and energy calculations.



Per product

Factor	Energy			Material			Emission/Waste type/target		Emission/Waste material	
	Coal	kg	0,00	Electronics	kg	1	Hazardous	0,05	CO kg	0,00001
	Electricity	kWh	3,55	Epoxy paint	l	0,1	Air	0,00032	NOx kg	0,0002
	Gas	l	0,00	Plastics LDPE	kg	1	Water	0	Paint l	0,05
	Oil	l	0,00	Steel Fe37	kg	5,44	Land	0	water vapour m3	0
	Petrol	l	0,00	Water	l	0,02		0	VOC kg	0,00011
			0,00	Wood	kg	0,7		0	CO_2	0
			0,00			0		0		0

Per year 32093,9 pcs/year

Factor	Energy			Material			Emission/Waste type/target		Emission/Waste material		
	Coal	kg		Electronics	kg	32093,93	Hazardous	1604,70	CO	kg	0,32
	Electricity	kWh	114081,88	Epoxy paint	l	3209,39	Air	10,27	NOx	kg	6,42
	Gas	l		Plastics LDPE	kg	32093,93	Water		Paint	l	1604,70
	Oil	l		Steel Fe37	kg	174590,97	Land		water vapour	m3	
	Petrol	l		Water	l	641,88			VOC	kg	3,53
				Wood	kg	22465,75			CO2		

Secondary/indirect emissions

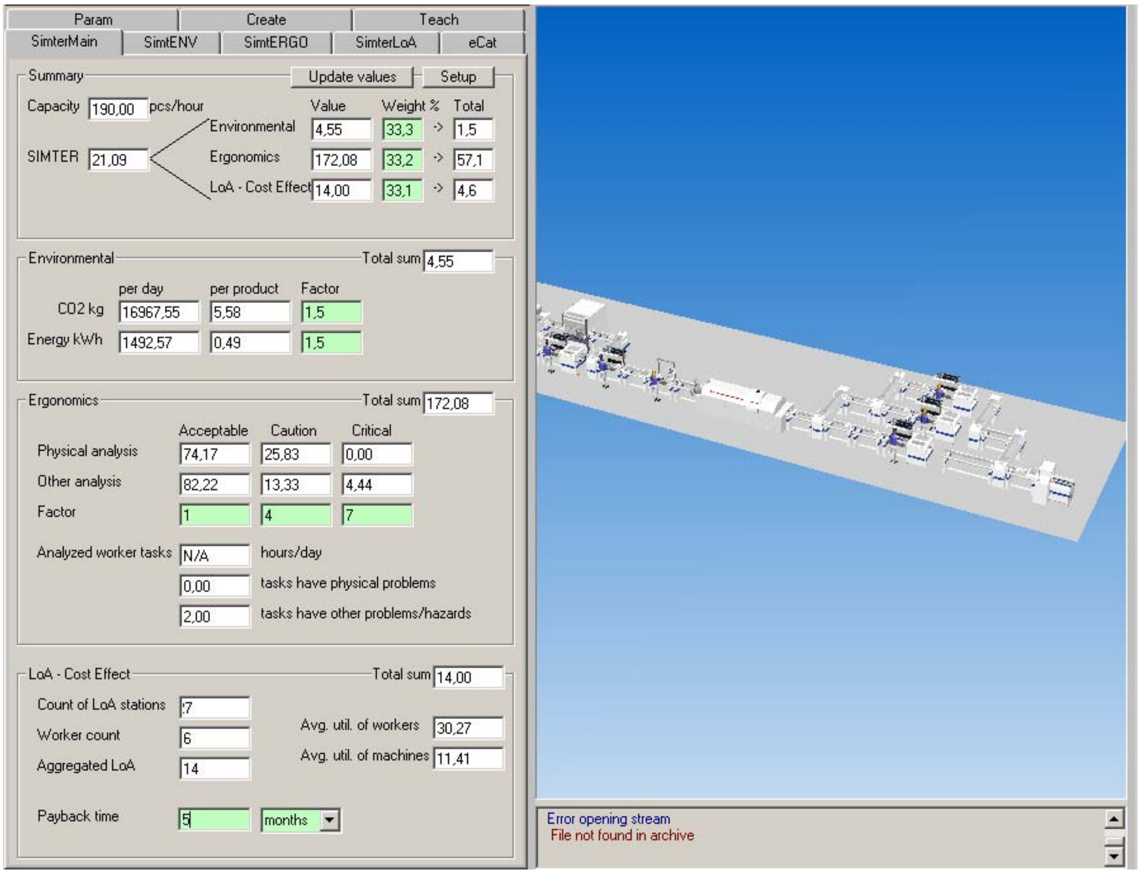
	CO_2 kg/unit	CO_2 kg/year		CO_2 kg/unit	CO_2 kg/year
Coal		0,00	Electronics		0
Electricity	0,193551	22080,66	Epoxy paint		0
Gas		0,00	Plastics LDPE		0
Oil		0,00	Steel Fe37		0
Petrol		0,00	Water		0
		0,00	Wood		0
		0,00			0
		0,00			0
Total CO2	**22,08**	**tons/year**			

Figure 14. Analysis results are shown per product and per year.

The simulation model calculates the percentage of machine states, idle, down, busy, repair, in simulated time. Similarly, energy needs in different states are known and the total energy need is calculated. In this case the simulation run was 672 hours, or 4 weeks. The results are shown per product and per year. The direct and indirect environmental impacts are also calculated.

3.3.6 Summary of the SIMTER analysis

The complexity while studying multidisciplinary parameter sets in simulation is high. Knowledge in many fields need to be incorporated. In an effort to give an overview of the results in a comparative manner from Figure 3, where it is stated that LoA, environmental impact and ergonomics are linked together. It means while changing one type of the input parameters in the model, other types of output measures can be affected. Figure 15 shows a summary of the results where the SIMTER analysis is presented in general indexed values. This is done in order to provide the user with a higher understanding on how changes affect the different types of parameters. E.g. by altering the LoA level from LoA mechanical 2 and LoA information 2 to LoA mechanical 6 and LoA information 6, we can say that the task at hand will be more human friendly since the ergonomic aspects will be removed. We can also say that it will have another environmental impact since we change the human to a machine. Finally, it will also change the scene for economics since we change the human operators high monthly cost to a high investment cost but with lower monthly cost. This example shows that all changes in the system can affect other not so closely related factors drastically.



Summary

Capacity 190,00 pcs/hour

SIMTER 21,09

	Value	Weight %		Total
Environmental	4,55	33,3	->	1,5
Ergonomics	172,08	33,2	->	57,1
LoA - Cost Effect	14,00	33,1	->	4,6

Environmental — Total sum 4,55

	per day	per product	Factor
CO2 kg	16967,55	5,58	1,5
Energy kWh	1492,57	0,49	1,5

Ergonomics — Total sum 172,08

	Acceptable	Caution	Critical
Physical analysis	74,17	25,83	0,00
Other analysis	82,22	13,33	4,44
Factor	1	4	7

Analyzed worker tasks N/A hours/day
0,00 tasks have physical problems
2,00 tasks have other problems/hazards

LoA - Cost Effect — Total sum 14,00

Count of LoA stations 7
Worker count 6
Aggregated LoA 14
Avg. util. of workers 30,27
Avg. util. of machines 11,41

Payback time 5 months

Error opening stream
File not found in archive

Figure 15. SIMTER Summary tab screenshot.

4. Discussion

The SIMTER project is a pioneering effort to introduce simultaneous, multi-parameter analysis for optimised design of manufacturing systems. The successful result of the project enables joint analysis of a) the level of automation, 2) ergonomics and 3) environmental impacts. All three analysis perspectives use discrete event simulation as a base for describing the analysed production system. The innovative SIMTER tool has been developed by the Finnish-Swedish research team and industries involved. It is an interactive computer-based system intended to help decision-makers use data and models to identify and solve problems and to make difficult decisions regarding sustainable manufacturing system design, especially in terms of social/human and environmental sustainability. The primary target user of the tool is a manufacturing system design engineer in a small or medium-size industry. Therefore special emphasis has been put on usability, to shorten the learning curve for the tool and reduce the price. Naturally, the SIMTER tool is equally useful for larger companies.

The SIMTER framework supports hierarchical analysis. This hierarchical approach of the SIMTER subtools is one of the key issues in integrating e.g. environmental and ergonomics subtools. The shared interests are e.g. energy, materials, wastes, exposures, additional/eliminated work tasks and, for productivity, the cycle times. However, specific details of shared interest may vary depending on the point of view. For example, from an environmental perspective the material or process may have excellent characteristics, but from an ergonomic standpoint it may be harmful. Precluding the conflict may require a special solution that needs checking also from the LoA point of view in order to reach an outcome that is acceptable overall. The shared interests and their databases as a common shared database between all the subtools are significant features that will provide a faster design and development process with better solutions.

The SIMTER tool will allow the production engineer to gain insight into the ergonomic impact of the production system by means of human simulation within the production model. It is known that both physical and cognitive aspects of ergonomics affect the humans' ability to perform the job correctly and efficiently, while maintaining one's health and safety. But within this area, the primary focus of the SIMTER tool is physical ergonomics. The tool is able to measure task duration and to compare results with ergonomics indexes (e.g. NIOSH, 1981; Waters et al., 1993; Snook & Ciriello, 1991; Liberty Mutual, 2007; OSHA, 2006; Garg, 1978). It will also enable reach, field of view and other physical factors analyses, including factors of occupational hygiene, such as temperature, noise and lighting. The possibilities of covering these aspects are plausible, and many of these aspects have already been implemented in the OSKU tool (see: Helin et al., 2007), a digital human model developed for participatory production design. That tool, featuring basic human simulation, was the starting point for SIMTER's ergonomics sub-tool. The work in SIMTER focused on the improvement of the motion database in OSKU.

Environmental responsibility has grown steadily as a corporate concern for the past decade. Increasing laws and regulations, coupled with the recognition that developing more eco-friendly manufacturing operations is “the right thing to do,” have put sustainability at or near the top of most companies' agenda. The rising costs of energy and climate change are also setting priorities for development. In the design of a new manufacturing system, engineers have normally focused on system productivity, capacity, and other key performance indicators of production. The environmental issues can be embedded in lean manufacturing system design as shown here. Johansson et al. (2008) have presented a case study in which a juice production process was modelled. The analysis incorporated both environmental effects and cost parameters. An Excel spreadsheet was used for presentation of input and output data. The SIMTER tool developed this concept one step further by actually providing an interface for environmental parameters directly in the selected simulation tool. In its current state, the environmental Excel workbook can be used for monitoring an existing manufacturing system, where real values from production can be entered instead of simulation results.

To incorporate environmental considerations while analyzing manufacturing systems, a shift of focus from economic growth to only a mix of parameters is needed. Lean is a step which incorporates waste in a positive way for both economic growth and environmental friendliness due to waste reduction activities. However, in order to measure waste and emissions towards cost parameters, a discrete event simulation model can be used as a sound basis for decision support.

When integrating the sub-tools, the biggest issue was identifying the set of shared variables and compatible performance metrics. In comparison to production optimization and environmental impact, as well as ergonomics and production optimization, which are easy to link and quantify, the relation between environmental impacts and ergonomics are more elusive and hard to quantify. The difficulty emerges from, for example, incompatible metrics (ethical issues cannot be expressed in monetary terms) and differences in time scales (short- and long terms costs and effects). Thus, the SIMTER tool focuses on the connections LoA-ergonomics and LoA-environmental impacts, helping the production designer to find the optimal solutions for the system design.

4.1 Future work

Along with the refinement of sub-tools, part of the future work will be showing feasibility and value of the integrated tool in practice. The integrated SIMTER tool will be developed to enable even more detailed and balanced analyses of production systems in compliance with the sustainable development paradigm.

In the SIMTER study, there were several specific challenges to be addressed with the joint simulation. Such challenges included e.g. balancing manual and machine work, reducing vulnerability of manufacturing systems to disturbances while maintaining low person-hour cost, determining the influence of levels of automation on ergonomics, and environmental impacts. Other needs included filling the gap between Life Cycle Assessment and conventional process simulation, and identifying the most significant environmental factors to be taken into account. Integration with manufacturing simulation provides a structure not just for measuring performance and environmental metrics, but also for identifying where action can be taken to improve "green performance". The above-mentioned features need enhancement in the future work, when the SIMTER tool is developed further. Along with the refinement of sub-tools, part of the future work will be showing feasibility and value of the integrated tool in practice.

5. Summary

The SIMTER project developed a discrete event simulation-based tool for manufacturing system design engineers to support optimization of sustainable manufacturing systems. The tool simultaneously addresses analysis of economic, social/human, and environmental sustainability. The SIMTER engineering environment integrated three sub-tools, enabling analysis of the Level-of-Automation (LoA), ergonomics analyses, and environmental impact assessment. The tool is meant to be used by small and medium size companies, but is equally useful for larger companies. All three analysis perspectives used discrete event simulation as a base for describing the analysed production system. The innovative SIMTER tool has been developed by the Finnish-Swedish research team and industries involved. It is an interactive computer-based system intended to help decision-makers use data and models to identify and solve problems and to make difficult decisions regarding sustainable manufacturing system design, especially in terms of social/human and environmental sustainability. The primary target user of the tool is a manufacturing system design engineer in a small or medium-size industry. Therefore special emphasis has been put on usability, to shorten the learning curve for the tool and reduce the price. Naturally, the SIMTER tool is equally useful for larger companies.

The literature review pursued in the project indicated that the type of joint simulation of ergonomics, level of automation, and environmental impact, being proposed in SIMTER, have not yet been reported. In addition, the company interviews conducted within SIMTER also indicated the practical need for the joint perspective on simulation for decision support. Moreover, the implementation work has indicated that such integration of sub-tools is technically feasible.

The level-of-automation (LoA) sub-tool helps to balance the task allocation between the human and the machine. Thus, it helps the production designer to search and compare the best solutions for the production optimization. The ergonomics sub-tool relies strongly on a digital human model, which enables a set of ergonomics assessments and checks on occupational safety. The ergonomics sub-tool helps to assess the physical and cognitive loads caused by the production tasks. Finally, the environmental sub-tool bases on GreenSCOR and EPA parameters, which are implemented on an Excel-worksheet. The environmental sub-tool summarizes a list on the environmental impacts (e.g. emissions to the air) caused by the production system.

In future projects, the integrated SIMTER tool will be developed to enable even more detailed and balanced analyses of production systems in compliance with the sustainable development paradigm.

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