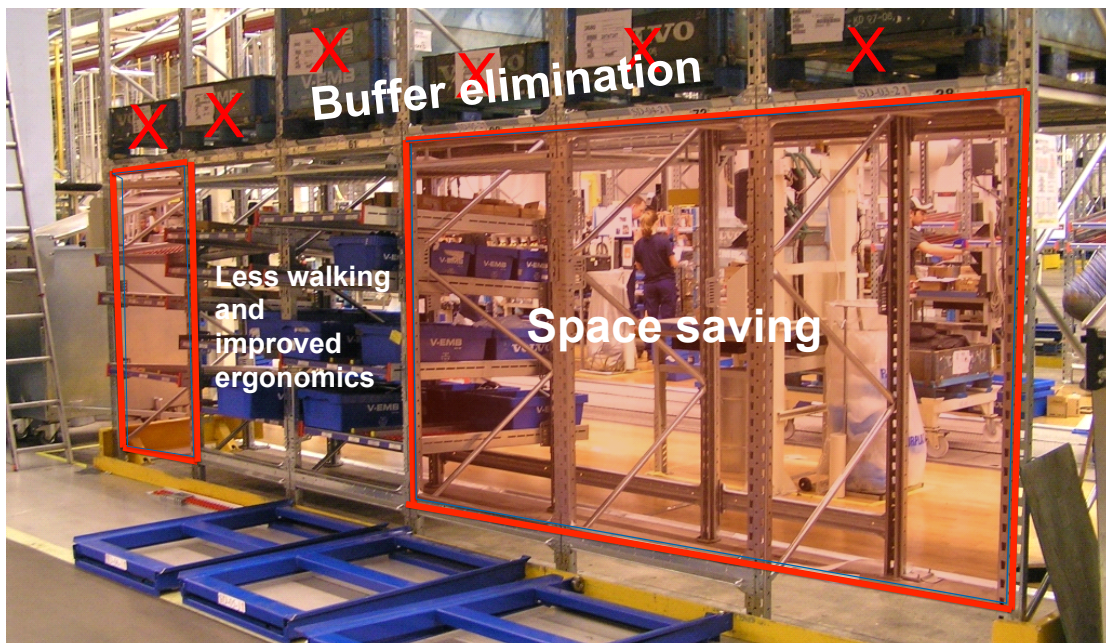


Sustainability and cost efficiency in Supply Chains



Project within Sustainable Production Technology

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FFI in short

FFI is a partnership between the Swedish government and automotive industry for joint funding of research, innovation and development concentrating on Climate & Environment and Safety. FFI has R&D activities worth approx. €100 million per year, of which half is governmental funding. The background to the investment is that development within road transportation and Swedish automotive industry has big impact for growth. FFI will contribute to the following main goals: Reducing the environmental impact of transport, reducing the number killed and injured in traffic and Strengthening international competitiveness. Currently there are five collaboration programs: **Vehicle Development, Transport Efficiency, Vehicle and Traffic Safety, Energy & Environment and Sustainable Production Technology.**

For more information: www.vinnova.se/ffi

1. Executive summary

The project was formed from three basic observations, which together considerably alter the requirements when designing the supply chains. First, the lean production deployment is now ruling the design of the work cells, e.g. the assembly stations. Second, the focus on sustainability and environmental consideration is calling for new models when designing the supply chains, and third, great cost and time reduction potentials are revealed in the supply chains when applying value stream mapping. This leads to a need for evaluation techniques and methods that cover a variety of supply chain alternatives, supply chain design methodologies, and decision support for developing lean and sustainable supply chains. Thus, the purpose of the project was to contribute to *the understanding and to the methods of how to design and evaluate sustainable and cost efficient supply chains that supports lean production processes*.

The project involved all industrial actors of the FFI programme and relied to a large extent on case studies performed in the companies. These cases often combined the development of models and methods with testing and pilot implementations at the companies. Results were disseminated among the actors through workshops and seminars, which further strengthened the results and understanding of applicability.

Among the theoretical contributions is the development of the concept of material exposure, as an interface between materials supply and assembly. This interface realizes the product of the material supply system in the form of an available component for the assembly system to assemble, given the requirements of the customer in form of the assembly system. These requirements govern how material exposure is realized and provides a framework for how materials supply systems can be designed. In this way, the principles of lean production in the assembly is supported by the material supply, while allowing the development of a material supply system that itself is lean.

One case study investigated systems for repacking of material between packaging types, that may be necessary to meet the requirements of the assembly system at the same time as the transport costs are kept down. From the case study, a classification of components that can be handled manually in this type of repacking were derived, and five different types of components were identified. The case study conclusions include the time to pick these components between different packaging types. These results have been put into further work in the case study company, regarding designing systems for repacking of material.

A theoretical model was developed to compare how the choice of packaging affect cost and CO_2 emissions for the supply of materials. A case study chose to compare two different packages with fundamentally different characteristics, one of which was a conventional returnable packaging based on plastics and the other a disposable one-way packaging. In this case the disposable packaging turned out to be clearly advantageous from both a cost and an environmental perspective.

A new methodology to describe and evaluate the fulfilment of requirements of material flows was developed within the sub-project ‘Materials Flow Mapping’. This methodology provides the ability to better, and in more detail, study material flows and its activities. Such a level of detail in the analysis proved valuable as a basis for improvement work in the materials supply system, where there is a need to be able to describe the often non-value-added activities that occur.

One sub-project was carried out with the aim of developing a cost model for estimating the cost of packaging, transport and in-plant logistics in a supply chain from suppliers to assembly, and to implement this in a software. This is an important contribution to the development of a decision tool for the selection of materials supply set up. The model represents a comparatively fast tool for obtaining cost estimates of various configurations of the materials supply system.

Finally, one sub-project has treated materials control, to support the research being done on the physical flows. The focus has been on pull-based materials planning with consideration to man, technology and organization (MTO), a need that was identified during the project. The result is two-fold, the first part being a model consisting of MTO factors that are important to take into account in the design and implementation phase of a pull-based system. Secondly, research has provided a better understanding of the potential problems during a process of implementing an external pull system and classified these problems based on the MTO dimensions.

In addition to the direct results, collaboration in the field have been significantly strengthened, e.g. through joint development initiatives, workshops and study visits in each other's operations. It has also led to the need for further research being identified. In regards to this, it can be mentioned that the use of the MFM model pointed to an considerable potential in reducing the administrative activities of the materials supply. Here, research is needed to identify deficiencies in current information systems, and to derive normative results concerning requirements of the proper system design. How materials exposure and the supply chain affect product quality have not been studied. Also, the informational aspect of picking support, in all parts of the supply of materials, has been found to have high relevance. Here, new techniques have been developed, but their effects in different situations are not resolved. The project has also identified many ergonomic issues and this aspect can supplement some of the developed models.

2. Background

The project “Sustainability and cost efficiency in Supply Chains” was built on findings from the MERA project “SwePS – Swedish Production System” (Vinnova Dnr 2006-00124), and on discussions within the MERA industrial cluster in “Logistics and materials handling”, thereby securing theoretical relevance and the treatment of contemporary industrial problems. The project was formed from three basic observations, which together considerably alter the requirements when designing the supply chains, and which had not been taken fully care of in research:

1. the lean production deployment is now ruling the design of the work cells, e.g. the assembly stations, and thereby the materials supply processes.
2. the focus on sustainability, in the sense of environmental consideration, is drastically calling for new models when designing the supply chains, in which sustainability variables are integrated.
3. great cost and time reduction potentials are revealed in the supply chains when applying value stream mapping, calling for exploitation.

The project considered the supply chain from the manufacturing companies' point of view, the OEM companies as well as the suppliers. This means that design aspects and improvements of the transport system was out of the scope. The supply chain was studied as a number of materials supply sub-processes, taking place within different organizations and at different locations.

Sustainable development has lately emerged as one of the main topics in society (Holm, 2007). World Commission on Environment and Development (1987) defines sustainable development as a development that meets the needs of the present without compromising the ability of future generations to meet their own needs, and containing three paths: ecological, social and economic sustainability (World Commission on Environment and Development, 1987). The basic foundations of Lean Production are similar to the definitions of sustainability, i.e. long-term philosophy and long term thinking with adding value to customers and society as a whole (Liker, 2004). Lewis (2000) treats the connection between competitive advantage and sustainability, and the use of continuous improvement (a core Lean production ingredient) to achieve sustainability. Thus, there is a good fit between sustainability and Lean Production philosophies.

Sustainability has lately become an important and emphasized research topic in logistics. However, the vast majority of this research is from the perspective of the transportation system and the transportation industry, which means that the issues at hand in the manufacturing companies when designing the supply chains are not fully taken care of. A few authors offer insight to the potential of developing supply chain related programmes for improving environmental performance and there is research on the topic of "green purchasing", involving supplier selection and supplier development. LCA models have been developed, taking transportation as well as production into considerations. However, this research is not well adapted to the decision situations of the supply chain personnel of the manufacturing companies.

Lean Production is a philosophy that stretches far wider than the name implies and extends to more areas of a company besides the core production processes (Liker, 2004; Monden, 1998; Ohno, 1988). Logistics research in which Lean Production is studied can be found in Baudin (2004), Hines and Rich, (1997), and in Jones, Hines & Rich (1997). In Lean Production, one basic principle is value flow orientation, but most focus in practice as well as in research has been on the area of value flow in production. However, the value flow orientation is equally important, and fruitful, in supply chains and operation and therefore more research is necessary of the value flow orientation impact on the supply chains.

Materials supply and assembly processes are two connected parts of the supply chain, each with its own rationales, creating a duality in the match between the assembly process requirements and the materials supply process interpretation of these requirements. In a Lean Production perspective, focus is on the supply chain value stream (Womack & Jones, 2003). From a lean production perspective, materials should be supplied in a steady flow in small batches, with supply being controlled by the actual consumption of the material at the workstation (Baudin 2002; Liker 2004; Monden 1998). Smaller supply quantities create a smoother flow and synchronizing these with assembly can be achieved by inserting the takt time in materials supply, by the same reasons as takt is used in assembly (Monden, 1998). However, this is often not the case in industry, where the materials supply processes have been based on principles contradicting those of Lean Production, meaning low frequent deliveries, large delivery quantities, extensive storages and buffers, etc. It is a need to better understand the impact different supply chain solutions have on the efficiency and in relation to sustainability aspects.

In lean production, an assembly operator should only perform value-adding work (Rother & Shook, 2003). Therefore, the material at an assembly station should be supplied in a steady flow and exposed favourably for the assembly operator, i.e. the materials exposure should be designed to aid the operator in creating value for the end customer. The materials supply process should be designed with these requirements in mind. However, despite the above description, assembly processes and materials supply processes have often been designed separately and with only little consideration to each other, leading to sub-optimizations (Tompkins et al., 2003). Instead, the materials supply process is designed with an efficient materials supply process in the supply chain in mind rather than the overall operations efficiency of the value flow or taking care of the requirements from the assembly process (Tompkins et al., 2003). Another example of this is the so-called “landed cost” models, in which many companies try to balance purchasing costs, transportation costs, etc. These models are having serious restrictions in their applicability when the assembly process is taken into account. Therefore, there is a need to better understand how different supply chain process designs impact the overall efficiency of the materials supply and assembly processes performance.

A transportation focus has also been the norm within logistics and supply chain, which has affected the choice of materials supply process (Tompkins et al., 2003). In Swedish automotive companies, purchasers and industrial engineers choose packaging almost solely from a small number of standardized packaging types, all of which are a module of the EUR pallet (800 x 1 200 mm). Packaging is mainly chosen based on belief in economy of scale and with the priorities to protect the components and to facilitate the transportation from the supplier, rather than being adapted to the operations in the supply chain. Thus, the actual way of designing the materials supply processes does not fulfil the requirement specified from the assembly processes, but rather is a solution-driven way of the most efficient way of supplying materials from an external materials supply point of view (Tompkins et al., 2003).

Hines et al, (2004) describes the sub-optimizations in supply chain design by stating the optimisation of such a networked system is determined by the value created for the customer, and not by performance measures within subsystems, such as the factory or the distribution channel. It is therefore, essential to be able to understand different supply chain solutions impact on the operations. Also, the SwePS project showed that there are a lot of storing and buffering activities between the supplier and the workstation at the assembly line. Each such activity, in turn, results in at least two handling activities, prolonged throughput time and increased work in progress, space requirements and decrease the flexibility to react to market changes, etc. It was concluded that there are great potentials for improvement in the supply chains of the Swedish automotive industry.

The above description shows a large potential to design more lean supply chains, but sets completely different requirements on current supply chains compared to the traditional way of supplying material, and introduces great challenges in terms of being able to consider and evaluate environmental performance in all design phases of a materials supply system. Consequently, the supply chains in the automotive industry are challenged, because of the Lean Production focus on maximising the share of value-added time in the value flow. Thus, there is a need for evaluation models of how the supply chain design impacts the sustainability and cost efficiency in a value flow (following the product flow along the supply chain).

3. Objective

In the production processes of the automotive companies in Sweden, a large number of changes are now taking place in order to adopt the lean production philosophies and respond to sustainability considerations, and this adoption is equally important for the companies' supply chains as such. Thus, the procedures of the supply chain design have to be further developed. When these issues are becoming of high priority, or the number one priority, the design of the supply chains has to be questioned. Are these designs effective in terms of supporting a sustainable development and the Lean Production philosophies, and, are the designs leading to supply chains that themselves adopt the Lean Production philosophies? For this purpose, it is necessary to create models to understand and to be able to evaluate different supply chains regarding the impact on sustainability and cost efficiency. Therefore, there is a need for evaluation techniques and methods, design methodologies and decision support for developing lean and sustainable supply chains.

Thus, the purpose of the project was to contribute to the understanding and to the methods of how to design and evaluate sustainable and cost efficient supply chains that supports lean production processes.

4. Project realization

The project heavily relied upon a number of deep case studies performed in the participating companies. These case studies were performed within two phases (1 and 3) of the project. In *Phase 1*, preceded by an *Initiation Phase*, cases were selected to reflect different and typical structural designs of the supply chains that relate to the scope of the project, and to include the challenges described in the background section. Phase 1 of the project led to a deepening and synthesizing analysis in *Phase 2*, which served the purpose of giving preliminary answers to the research problems, deepening and reformulating the problems, and to add issues that during Phase 1 were found to be of great importance in order to fulfil the purpose. The development of generic models takes place in parallel with the case studies. This phase resulted in proposed models.

The second set of cases, performed in *Phase 3* of the project, served the purpose of providing input to the reformulated and deepened problems emerging from the previous phases, and to refine and validate the proposed models.

Phase 4 of the project dealt with finalizing and dissemination of results, although dissemination activities very much took place also during the project. For example, Phase 1 resulted in detailed case descriptions that were of great interest to many companies, and were used as input into the workshops within the project. The generalized work pattern in each case followed the structure below:

1. Case project initiation, including work packages, detailed time schedule and organization
2. Main study and preliminary analysis
3. Presentation of preliminary results to the whole project group, including representatives from all companies participating in the project, in workshops and/or project meetings
4. Gathering of additional data, if necessary, and refined analysis
5. Presentation of results in the project group, including a discussion on validation and generalization, and identification of further questions rose from the results.

5. Results and deliverables

The project and its case studies have delivered a number of results at different levels. The case-study "Packaging downsizing" studied how the company in their own factory can repack components from large packages adapted to external transportation, into packaging adapted to the internal supply of materials and material exposure at the assembly station. The requirements of the assembly station can greatly differ from those of the external transport. From the case study, a classification of components that can be handled manually in this type of repacking were derived, and five different types of components were identified. The case study results include the time it took to repack these components between different types of packages. These times have already been translated into further work in the case study company, in form of new ways to repack

materials, as well as in educational material and as input to new improvement work at the company.

The case study ‘Selection of packaging systems in supply chains from a sustainability perspective’ was conducted across an entire supply chain from supplier to point-of-use in an assembly plant. The case studied how the chosen package for materials exposure affected the materials supply system in terms of cost and sustainability. A theoretical model was developed to compare how different packaging options affected in terms of cost for material supply and CO₂-emissions. The case study compared two different packages with fundamentally different characteristics, one of which was a conventional returnable packaging based on plastics and the other a disposable one-way packaging based on cardboard. Case study results showed several interesting conclusions. First, the model developed showed applicable and generalizable, and secondly, the often established convention that it is both environmentally and cost wise better to use returnable packaging was dismissed in this case. The case study showed clearly that in the selected case was better both from a cost and environmental perspective to use a disposable packaging.

The multiple case study ‘Extended Value Stream Mapping’ took as its starting point the need to be able to describe the often non value-adding activities that occur in supply chains. Which are these activities and how do they conform to the requirements on the flow? A methodology for describing materials flows and identify the requirements on the flow was developed in the case study, which collectively studied seven flows involving 22 companies. Using the methodology enabled detailed descriptions of the flows and the requirements established in these. The methodology was designed to appropriately describe the flows as a basis for evaluation, design and improvement of the same. Moreover, it appeared that performing the studies, i.e. using the methodology, created a significantly increased interaction between the companies of the supply chain. The methodology was also used in the two case studies described above, as well as in a number of student projects.

Several student projects have contributed results to the project, and experiences from the project have been disseminated results within education programmes. The student case study projects ‘ECO-tool’, ‘Flows of returnable packaging between Volvo Logistics and customers’, and ‘Product Flow Analysis - component manufacturing to final assembly Volvo Powertrain’ resulted in reports that could be utilized in the operations at the case study companies. ‘ECO-tool’ tested and developed an IT-based tool as the case study company itself drafted. ‘Returnable packages’ was studied in a master thesis at Volvo Logistics, which focused on cost and environmental aspects of washing returnable packaging. The latter study also provided input for the case study regarding the above-described model for choice of packaging system. Additionally, a full course of students (Lean production within Master of Prod Engng) studied several flows in the manufacturing of components at Volvo Powertrain, and mapped the flow of materials with the methodology developed within the extended material flow analysis. Another master thesis has studied the packaging in materials exposure for small-size materials, and how this affect the materials flow from the supplier to the assembly line in the assembly plant.

A student project group in the course ‘Projects in Production Engineering’ analysed, by using the MFM methodology, the production processes and material flows of four product families at Volvo Powertrain in Skövde. The project resulted in four suggestions, one for each product family, on how to improve the current situation. One of the suggestions was later implemented in the factory during a master thesis conducted by two of the student project group members.

One sub-project was carried out with the aim of developing a cost model for estimating the cost of packaging, transport and logistics within production plants in a supply chain from suppliers to assembly, and to implement this into a software. This was intended to contribute to the development of a decision tool for choice of materials supply system configuration. Since the result from using the software for cost estimation is calculated from a database that is unique to the company for which the software has been adapted, it is possible to discern details such as shipping method, distance to suppliers in terms of country and postal code, and annual volumes received from a specific supplier as output in a summary of the results. This allows the user to obtain an overview of the different properties of the specified supply chain, which facilitates insight and understanding of aspects such as sustainability. However, cost efficiency is the primary evaluation variable in the model and the cost estimations obtained as results are consistent with calculations made with manual estimates by the company at the time of the project. As the emphasis of the program is cost-effectiveness, the degree of fulfilment of the requirements for the supply chain is not considered in the software. Instead, intended use of the software is at the time when the various solutions that have already been verified to fulfil the requirements are compared with each other. An assessment of the degree of conformance to the requirements can be made using the MFM method. The model represents a comparatively fast tool for obtaining cost estimates of various configurations. At the time of finalization of the sub-project, the software was in use at the company. Additionally, efforts to adapt the software for use at other production sites have begun in collaboration with the research group.

One sub-project was conducted in order to test and evaluate the method ‘Materials Flow Mapping’ (MFM). The sub-project concluded that the MFM method is a relatively fast and accurate method to detect potential improvements in existing materials flow systems. The so-called materials flow maps of the studied materials flows could be used to increase knowledge and understanding about the actual situation of the processes studied, and for the sustainability aspect of the supply chains. This knowledge may ultimately be used to improve communication and awareness of the system among both management and material handling personnel, which is an important aspect of the business if sustainability is pursued.

Research on the selection of materials supply method shows which factors are important to consider as well as which factors that are used in industry. In a case study a company in the automotive industry (VCE) was studied during the work of developing a tool for the selection of materials supply method for a specific component. This study resulted in a better understanding of which factors are important to consider, and increased the understanding regarding the development of such a tool.

The area of *materials control* was included in the later part of the project, to support the research performed regarding the physical flows. The focus has been on pull-based materials planning with regard to man, technology and organization (MTO). In a pull-based materials planning system, there is usually a high degree of human interaction, which means that, e.g., assemblers, materials planners, and storage staff, not only need to be physically involved in the system, but also have a participatory role in the materials planning process. This may increase the risk of errors caused by individuals, and may also contribute to a more complex social system as cooperation between departments is necessary. An external material planning system that involves more than one organization could be even more complex. Therefore, there is an interest to explore how man, technology and organization interact and affect the outcome of such a system.

The results of the research on design and implementation of pull-based systems is twofold. The first part is a model consisting of factors relating to man, technology and organization that are important to consider in the design and implementation phase of a pull-based system. This model can be used for further research, and as a checklist for managers in industry in the process of designing a pull-based system. Furthermore, research has provided a better understanding of the potential problems during a process of implementing an external pull system and classified these problems according MTO dimensions. Moreover, the study has shown how the focus in the initial stages of the implementation process can affect the later phases of the process. The results suggest that it may be harder to predict problems of man and organization, despite the fact that these areas were the focus of the case study company during the first two stages of the process. Moreover, it seems that these problems take longer time to solve, implying that they are important to include early in the implementation process. In other words, the results show the importance of including human and organisational aspects early in such a project, in the same way as technical aspects are included. This is particularly important when designing a pull-based system spanning more than one organization.

6. Dissemination and publication

6.1 Knowledge and results dissemination

Results and experiences from the project have, in addition to occasions internal to the project, been communicated at:

- Seminar, Delft University of Technology, October 2009
- Presentation at VTI Transportforum, Linköping, January 2010
- Monteringsforums conference, presentation, March 2010
- Seminar with Smålands produktivitetsförening, Jönköping, March 2010
- FFI-dag, Scania, April 2010
- Workshop within Fordonskomponentgruppen, Chalmers Lindholmen, May 2010
- EurOMA conference Porto, June 2010
- Workshop with focus on repacking and picking support, Volvo Cars, September 2010

- Workshop with focus on kitting, SAAB Automobile AB, Trollhättan, September, 2010
- FFI conference, Tekniska mässan, Stockholm, Oktober 2010
- Workshop at Scania, Oskarshamn, October 2010
- FFI-dag at Volvo Cars, Gothenburg, February 2011
- Monteringsforums conference, Stockholm, March 2011
- Workshop on logistics centres,- DB Schenker, Business Park Arlanda, April 2011
- SPS, Swedish Production Symposium conference, Lund, May 2011
- Logistik och transportmässan, Gothenburg, May 2011
- Workshop with focus on relocating production, Gothenburg, May 2011
- NOFOMA Conference, Harstad, Norway, June 2011
- EurOMA Conference, Cambridge, Great Britain, July 2011.
- ICPR Conference, Stuttgart, Germany, August 2011
- PLAN's tillämpnings- och forskningskonferens, Norrköping, August 2011
- EurOMA Conference, presentation at conference and participation in PhD workshop where project results were discussed, Amsterdam, Netherlands, July 2012
- AB Volvo dissemination conference within FFI projects, Gothenburg, October 2012
- Volvo Research Foundation conference, where the project contributed a presentation regarding material supply and problems in common with city logistics, October 2012.
- Workshop with Volvo Cars regarding software for cost estimation of supply chains, Gothenburg, June 2013
- NOFOMA Conference, Gothenburg, June 2013
- EurOMA Conference, presentation at conference and participation in PhD workshop where project results were discussed, Dublin, Ireland, June 2013

Within education at Chalmers, project results and experiences have started to be integrated into courses in Production Logistics, Lean Production, and Projects in Production Engineering in the Master program of Production engineering, and within the courses Material Handling and Production Flow, Production Flow Management, and Projects in Supply Chain Management in the master program of Supply Chain Management. Results have also been added to the previously established course in Lean Production, within continuing education.

6.2 Publications

Algestam, S. (2013). Implementation of external pull systems – a case study in the automotive industry. *Proceedings from the 20th EurOMA Conference*, Dublin, June 2013.

Algestam, S., Medbo, L., Wänström, C. (2012). Designing a pull oriented material planning system - human, technical and organizational considerations. *Proceedings from the 19th EurOMA Conference*, Amsterdam, July 2012.

Algestam, S., Rosenberg, P. (2011) Supplier consequences of variation in demand planning information: An automotive industry case study. *Proceedings of PLANs Forsknings- och tillämpningskonferens 2011*, Norrköping, August 2011.

Andersson, A. and Norman, B. (2013). *Effektivisering av stödprocesser: En studie i lean materialhantering*, Master of Science Thesis, Linköping University (in Swedish).

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- Fager, P. (2013) *Supply chain cost estimation, Excel-based software*, Division of Logistics and transportation, Chalmers University of Technology.
- Fager, P. (2013) *Handbook for Supply chain cost estimation software*, Division of Logistics and transportation, Chalmers University of Technology.
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- Godarzi, S., Sampka, A., (2010), *Small material replenishment at Volvo Powertrain: Implementation of two-bin system for carton containers at Volvo Powertrain in Skövde, Sweden*, Master of Science Thesis, Report No. E2010:008, Chalmers tekniska högskola.

- Gunnarsóttir, D. R., Valdimarsdóttir, M. G., (2012). *Material availability at point of use - Multiple-case study in the automotive industry*. Master of Science Thesis, Report No. E2012/058, Chalmers tekniska högskola.
- Hanson, R., Finnsgård, C., (2011). Impact of unit load size on in-plant materials supply efficiency. *Proceedings of the 21st ICPR conference*, Stuttgart, July 2011.
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7. Conclusions and future research

Several conclusions, both theoretical and practical, can be drawn from the project. Among the theoretical contributions is the development of the concept of material exposure, as an interface between materials supply and assembly. This interface realizes the product of the material supply system in the form of an available component for the assembly system to assemble, given the requirements of the customer in form of the assembly system. These requirements govern how material exposure is realized and

provides a framework for how materials supply systems can be designed. In this way, the principles of Lean Production in the assembly can be supported by the material supply, while allowing the development of a materials supply system that itself is lean.

At the assembly station, it can be concluded that material exposure affects performance in three areas: space requirement for materials, the proportion of value-added work, and ergonomics. The case studies showed a significant impact in all areas and a change of material exposure resulted in one of the cases to a 20 per cent productivity increase in the assembly system. On a detailed level, it was further studied how a number of factors in material exposure affect the assembly operators' time to pick components. The result can be used to assess the potential for improvement or the expected difference between alternative exposures at an assembly station, or an entire assembly system. The factor that affected the picking time most was the packaging design, followed by the angle of the packaging, and third, the height of the exposed components.

How material exposure is designed also affect the resources required to realize the material supply. It is widely believed that large packaging provide the most efficient material supply. The project results show that the required resources do not have to be proportional to the size of the package, but that small and customized packaging, adapted for the assembly and having high delivery frequency, can be supplied as efficient as larger packages (e.g. EUR-pallet). Ergonomic aspects upstream the materials flow due to the new and realized requirements have not been studied in the project, but has been identified as essential for further research.

A new methodology to describe and evaluate the degree of fulfilment of requirements of materials flows was developed within the project, Materials Flow Mapping (MFM). This methodology provides the ability to better, and in more detail, study materials flows and its activities. Such a level of detail in the analysis proved valuable as a basis for improvement work within the material supply system. The methodology developed in this project would be possible to extend to include also the description and evaluation of ergonomics and environmental aspects of the flow. The model can also be further developed to include a methodology that actively supports how improvement efforts are applied, i.e. the "future state" of the materials supply system. Further, the results obtained from using the model pointed out considerable improvement potential for administrative activities in the supply of materials. This calls for further research to identify gaps in existing information systems, and provide normative results concerning proper system design.

A model was developed for the evaluation and comparison of different packaging systems, to select the most appropriate from cost and environmental perspectives. The model shows the variables to take into account when choosing between packaging options. The case study showed great potential to significantly reduce CO₂ consumption in the supply chain. Currently, no estimation is made in the case study company regarding the environmental load stemming from the choice of packaging, and the model may therefore have a very high value. A case study of a materials flow revealed that a disposable one-way cardboard packaging in this case was better both from an environmental and a cost perspective compared to a returnable plastic container. Per component

that was supplied to material exposure in assembly, the potential for improvement was 0.37 Euro and 208g of CO₂. These methodologies and models together provide powerful tools to design new and improved materials supply systems within the Swedish automotive industry and more sustainable production of new vehicles.

The project results have contributed to several new ideas for further research, partly as deepened research based on the conducted research, as well as expansions within the studied areas, and on new aspects identified within the project work. The research on how materials exposure affected the performance of the workstation has identified several needs for further research. One parameter that was outside the conducted studies is how material exposure affects product quality of finished products. Furthermore, one can extend the study of picking times to include additional factors that can affect picking time. The study carried out in the current project was delimited, and the factors that were not selected to study could be further studied. An example is the properties of the packaging. A case study can at a more detailed level examine how packing characteristics affects picking time. This is perceived as significant because the results now available indicate the packaging to be the factor with the single largest impact. Likewise, it should be interesting to further study how the density of the material exposure affects picking time. How an exposure of material without packaging (known as *minomi*) affects picking time can also provide interesting contributions, due to it being an approach that has gained increasing industrial interest, but increases the number of activities in the supply chain. How the total economy and quality are affected are not yet investigated.

An additional area of the project that has shown to have very high relevance is the information aspect of the order picking support, in all parts of the supply of materials (including the assembly station). Here, new technologies have started to get a foothold, but their effects and suitability in different situations are not resolved.

The tool for cost estimation of the supply of materials that was developed in the project were found to have high validity and allow for quick evaluation of configurations of the supply chain, for individual parts or groups of parts. Further development of the software should be to simultaneously evaluate environmental impact, e.g. in the form of CO₂ emissions. The result can be used as a decision variable in addition to the cost, but availability of required information must be investigated. Also, development of standard methods for the collection of data to and organization of the software database would be valuable, and to further refine the user interface and the algorithms used to manage data.

The results of the research on materials supply systems and planning has clearly shown the importance of taking into account man, technology and organizational aspects. Although the research is primarily directed towards pull-based control systems, the results should also be applicable to other methods, although the human elements is suspected to have the greatest impact in pull-based systems (higher degree of decentralization and human involvement). The project has not included the operational phase, but focusing the design and implementation phases, which points towards a natural continuation of the research. Moreover, the model developed should be validated in a larger number of materials flows.

8. Participating parties and contact persons

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