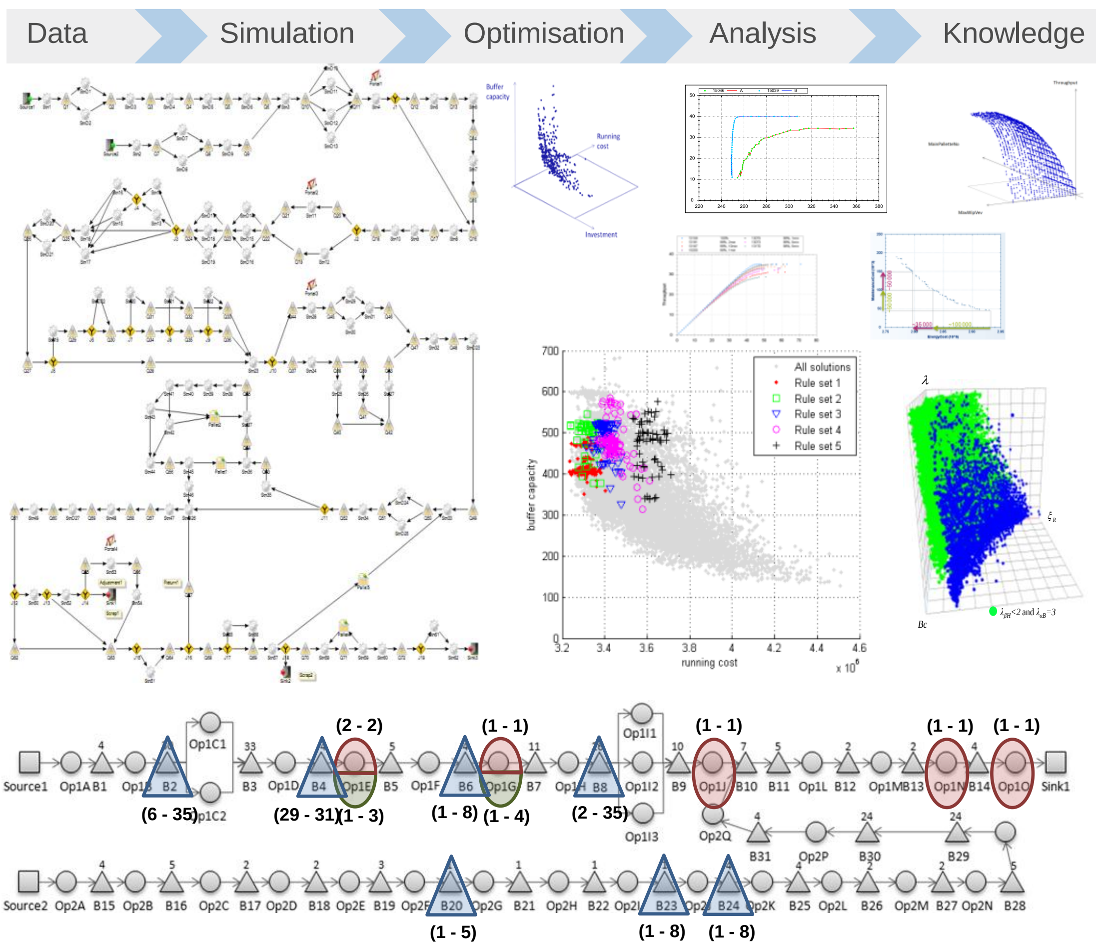
Holistic Simulation Optimization for Sustainable and Profitable Production (HSO)



Project within Sustainable Production

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Content

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.**

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Executive summary

Sustainability, in terms of "Energy Efficiency" , "Lean", "Lead Time Efficiency" and other forms of reuse/conservation of resources has become a paramount factor that needs to be considered not only during the operational stage but from the very first day a production system is designed. At the same time, there is an urgent need for the Swedish manufacturing industry to explore strategies and methods to accelerate the industrial efficiency progress and support decision making in order to regain profitability. With this as the core motivation, the FFI-HSO project was started in September 2009, with an aim to explore and develop a new manufacturing management and decision support methodology, or so-called HSO methodology, as illustrated in Figure 1, based on the state-of-the-art simulation-based multi-objective optimization (SMO) technology. The very concrete and successful results of HSO can be demonstrated from a business case study completed at VCC in 2011.

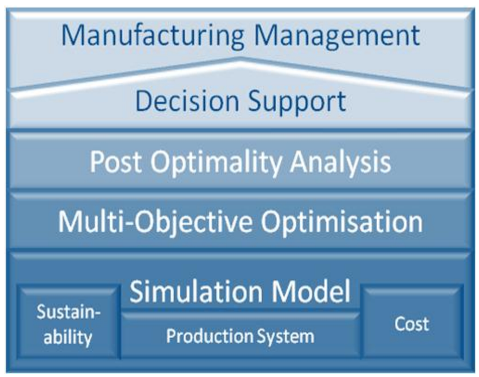

Figure 1. HSO framework for manufacturing management and decision support.

In this business case study of the re-design of an automotive components machining line, the main objective of the company was to achieve a 20% increase in production capacity but at the same time 20% running cost reduction. In other words, the challenge was to identify the optimal investment alternatives that could increase the throughput, but simultaneously reduce the running cost as much as possible. The potential of applying SMO and post-optimality analysis (see Figure 1), taking into account productivity, financial and sustainability factors for decision-making support, as proposed in HSO, had been explored and proven to be very beneficial for this kind of industrial applications. Evaluating several combined minor improvements with the help of SMO had been used to identify a set of solutions (designs) with great financial improvement, which were impossible to be done by any other industrial procedures. Unlike many other research case studies, we got the opportunity to validate the SMO results because the production manager of the target plant had decided to implement the solution proposed from the case study. The validation showed that, with an one-off investment cost of 1.1M SEK, overall throughput of the machining line was improved by 20.9% and the cost performance on annual basis was improved by 26.5% and energy consumption reduced by 12-15%. If we consider the definition of productivity as Output/Input, then with the improved output (number of products per year) and simultaneously less input (resources or cost), then the increase of productivity in this case study was actually 36%. Behind this successful case study was an innovative way of embedding many improvement potentials into the simulation model of the production line so that the best combinations are sought and analyzed using the algorithms explored in the project. This approach is also unique from a scientific research perspective because, to our best knowledge, using SMO to identify optimal improvements to manufacturing systems has never been proposed.

The HSO research team has been very active in scientific publications during the entire project period. With the aim to disseminate the concepts and results from the project, altogether there are over 32 publications published or submitted during the project period. Apart from publishing in international peer-reviewed journals, the quality of these publications can be reflected by the fact that two papers received the best paper award in the conferences that the papers were presented. More information about our scientific publications can be found in Section 6.1. Regarding further results dissemination to industry, we strongly believe that industrial workshops and courses represent the most effective form. Particularly when the courses are not about Powerpoint teaching, but on practical hands-on to use some toolset developed from the research. Through the course Production System Development (7.5 ECTS) jointly developed together with VCC, some 200+ engineers have already gone through some basic training in SMO and a one-day workshop on using the HSO toolset to explore production system development concepts. This form of results dissemination is now planned for at least 1 more course started in 2013, as it will be further explained in Section 6.2.

Background

In connection to the current adaption to more CO2 efficient powertrains and vehicles, the automotive industry must change-over to the production to new fuel-saving products, including other variants and components than in current production. As a result from this, regaining profitability is not just a matter of “simply” running current production in a more efficient way. Industry is facing many important decisions in designing or re-configuring production facilities to accommodate this increased number of variants. These decisions are extremely important since they tend to lock around 80% of cost of the investment and operation costs. In other words, if the optimal alternatives are not explored and considered so that non-optimal decisions have been made in the early stages, then the investment cost will be significantly higher and the operational costs of a production system affected throughout its whole lifecycle.

The common industrial practice today is to make important decision based entirely on the experience from existing processes and static estimation tool. With the abundance of data collected and saved in industry today, it is possible to perform detailed analysis on an existing process. Nevertheless, when it comes to making important decisions for the design/re-configuration or system improvement of a production system, then the decision makers are very often caught into the problem of sifting the right and accurate information out of the data ocean – the so-called data haystack syndrome.

On the other hand, it is often said that simulation is the most promising tool to support decision making in production systems design. Simulation engineering has since long been believed to be an enabling technology for life-cycle decision support. It is widely accepted that simulation is the only general purpose and generally applicable modeling tool for truly complex systems. Particularly, it is an extremely valuable tool for tackling problems that cannot be modeled by classical optimization methods. Quantitative performance evaluation in industry is in almost all cases carried out using simulation. However, despite that simulation holds tremendous promise and possesses a strong and established background, manufacturing industry has been less successful in using it as a decision-support tool. In other words, while simulation is used more frequently today in industry, it is more often used when important design decisions have already been made and costs are locked without exploring any possible better alternatives and their parameter settings in the production system industrialization process. There are mainly two reasons:

1. So far, despite simulation software packages have gained much more popularity, the knowledge and expertise to develop simulation models is still not trivial. Managers who take decision-making responsibility seldom possess the skills/time to develop simulation models and then run experiments directly in order to draw significant conclusions for making important decisions. It is a common practice to hire other simulation specialists in the company or external consultancy firms to carry out the experiments and formally report the results. Since this would seldom be completed in a single pass, in addition to the higher costs, the long lead times involved may prohibit the interest in using simulation for decision-making support.
2. Using simulation alone is not sufficient to yield optimal solutions. Simulation by itself is not a real optimization tool and "an extra step is needed – a step that joins simulation and optimization". Traditionally, design of experiments (DoE) is the major method used to find optimal solutions with the use of simulation models. However, DoE requires also intricate specialist knowledge and furthermore, extracting knowledge from simulation experiments is still a task that relies heavily on persons with deep knowledge of both simulation engineering and the system under study.

Based on the above discussions, the problems of the current industrial practice in decision making for production systems design/re-configuration and improvement can be summarized with the help of Figure 1 below.

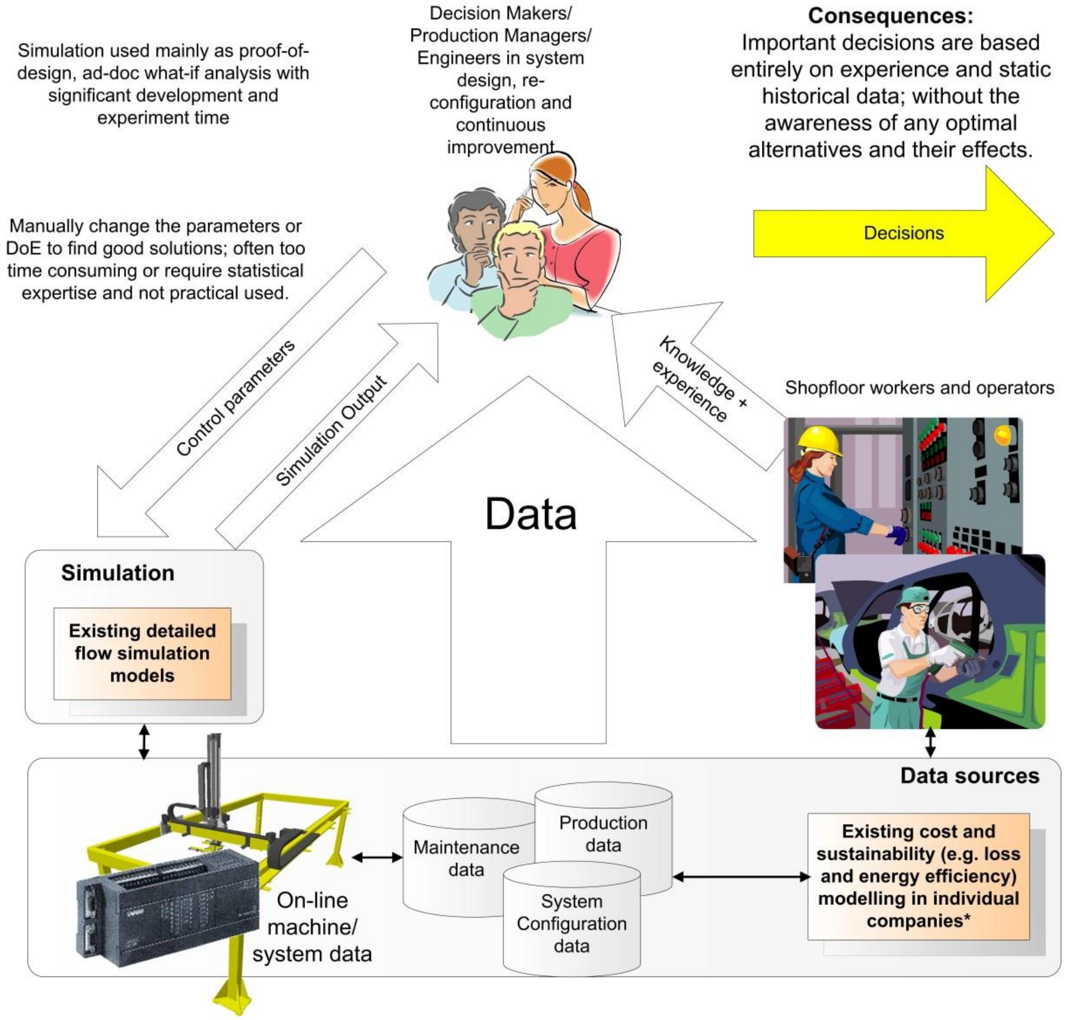

Figure 2. Current industrial practice in decision making for system design/re-configuration and improvement.

Objective

The overall aim of the project is to increase the profitability (increasing cost effectiveness) and simultaneously sustainability (increasing energy efficiency, reducing losses/wastes and shorten Order to Delivery Time) of the Swedish manufacturing industry through the research and development of an innovative robust optimization and knowledge elicitation methodology (the HSO methodology) for decision-making support within the production systems lifecycle.

The industrial and scientific objectives derived from the project aim are listed below.

1. To extend existing sustainability and cost models and to integrate these into detailed simulation models to provide holistic modeling capability for system optimization and improvement that takes into account productivity, cost and sustainability.
2. To reduce the engineering time spent in system design and analysis significantly through rapid modeling and automatic optimization.
3. To automatically identify bottlenecks so as to indicate where to prioritize and start the improvement, both by using the integrated simulation optimization models that take productivity, cost and sustainability into account within a MOO context.
4. To apply new scientific methods to identify and optimize the most important parameters in both system design/re-configuration and continuous improvement processes.
5. To capture important knowledge, in terms of best design principles and decision variables correlations so as to obtain a general understanding of good production systems design to increase the companies' overall competiveness.
6. To study the concept of "innovization", i.e. knowledge discovery through post-optimal analysis, from the MOO and simulation data using data mining techniques.

1. Project Realization

The HSO methodology is realized through the development of a software toolset that synergistically integrates Discrete Event Simulation (DES) with the sustainability and cost models developed by individual industrial partners with state-of-the-art SMO and data mining (DM) technologies, to support the knowledge-based decision making in production systems design, re-configuration and continuous improvement. Figure 2 illustrates such a proposed HSO system structure. The HSO system contains four sub-systems: 1) data sources; 2) simulation; 3) multi-objective optimization and; 4) innovative knowledge elicitation. Such a system design is based on the HSO concept that knowledge should be extracted from robust Pareto-optimal solutions obtained from multi-objective simulation optimization. When comparing Figure 2 to Figure 1, it can be noticed that HSO proposes an innovative production data management paradigm, namely, data→simulation→optimisation→knowledge, which is believed to be an efficient way to manage, process, optimally use and reuse companies' data than today's common practice. As illustrated in Figure 2, different HSO sub-systems feed different types of information to the users (decision makers). The size of the arrows in the figure represents the weight of importance of the information that decision making are based – decisions are made based more on higher-level knowledge (e.g. in form of decision trees/rules), optimal robust multi-objective solutions, simulation outputs than lower-level data coming directly from the "data haystack".

In contrast to today's DM technology, "knowledge" is extracted from robust optimal solutions obtained through SMO, instead of directly from data collected from various data sources in the company. This novel concept, known as "innovization", was regarded as the one of the research challenges in the project.

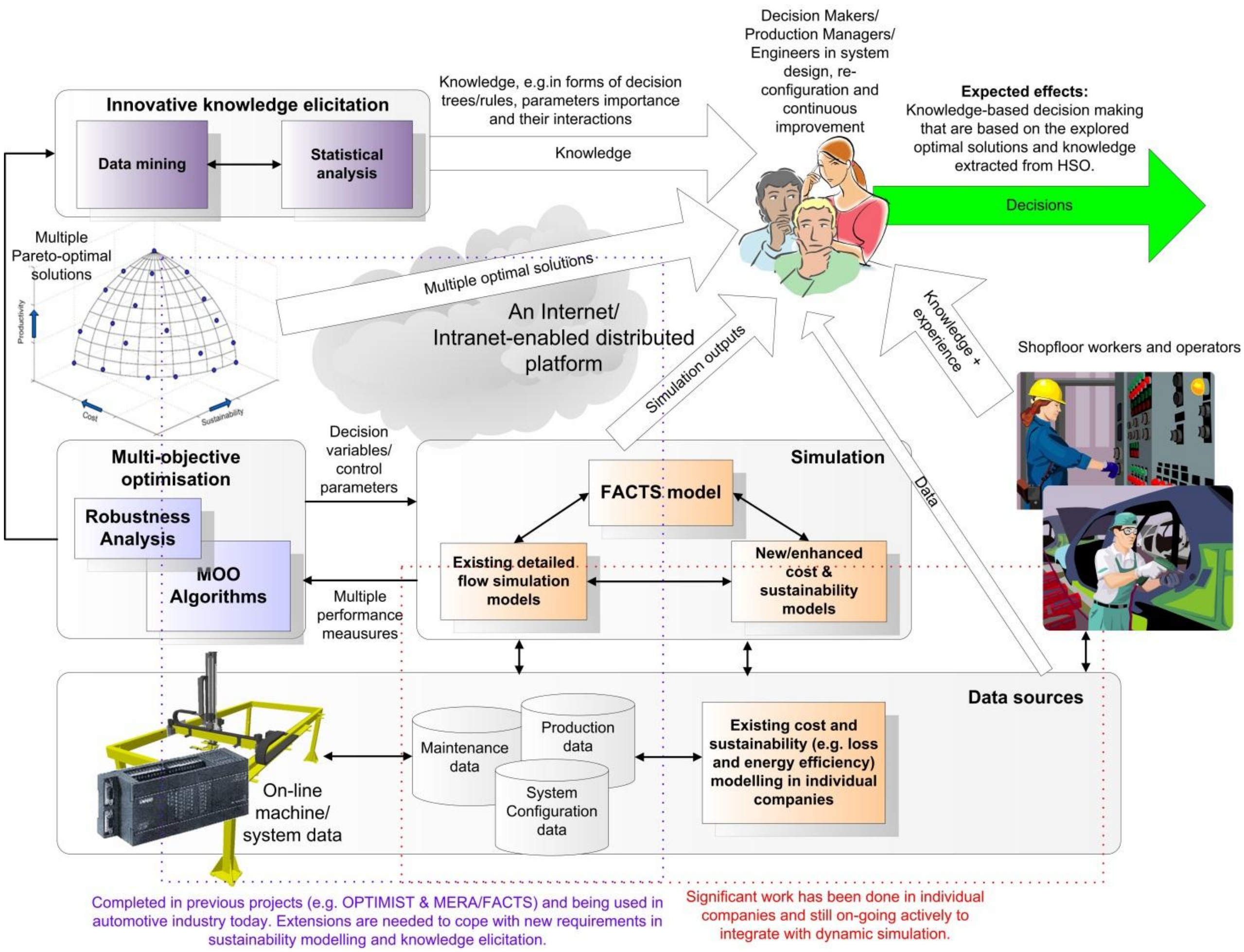

Figure 3. The HSO system structure.

The project was conducted in three different phases as presented in Figure 4: (1) Business cases; (2) HSO system development and (3) HSO customization. In phase 1 the HSO concepts were tested in several business case studies at the partner company, using prototype tools or off-the-shelf software modules, before the full HSO system development (Phase 2) was commenced. During the deployment of the HSO results into industry in Phase 3, the HSO methodology has been customized to tailor for the specific needs/requirements of individual partner companies.

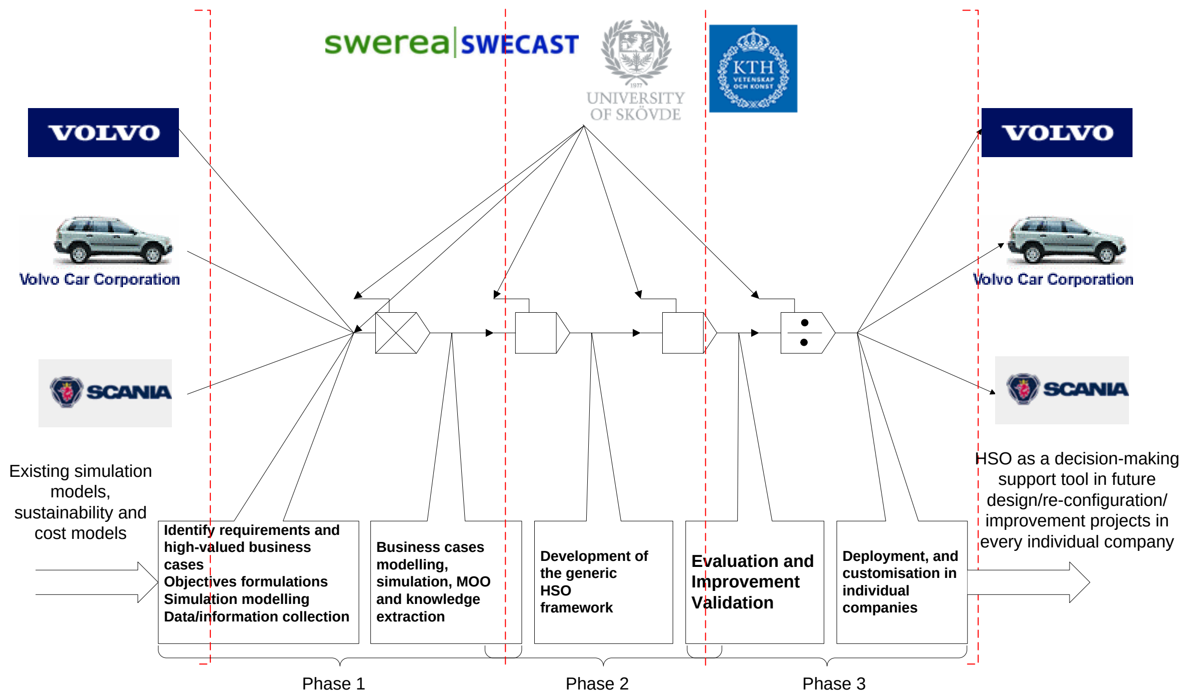

Figure 4. The project flow.

Results and deliverables

The concrete results of FFI-HSO can be summarized as below:

- A simulation model abstraction and data modeling methodology which takes into account productivity, cost and sustainability and its augmentation to the simulation models developed by the companies or rapidly developed with FACTS Analyzer for performing optimization and knowledge elicitation.
- HSO has successfully developed the methods and explored the off-the-shelf algorithms to extract knowledge from SMO. These algorithms, called Simulation-based COnstraint REmoval (SCORE) and Simulation-based Innovization (SBI), can be used to automatically detect bottlenecks, automatically identify improvement potentials and support decision-making in a highly interactive and innovative manner.
- Several successful case studies in the project with the partner companies have proved that huge cost reduction and significant energy saving in production can be achieved by using SMO technologies in an innovative way.

- The continuous development of FACTS Analyzer 2.0, the software tool developed first in the MERA program for supporting factory design, analysis and optimization during the conceptual design phase, is completed. It is extended with various new features to enhance its usability for rapid modeling of production systems and some manufacturing supply chain scenarios.

The “HSO toolset” mentioned in the original HSO proposal is delivered as two main software modules, now being used by industry, namely, *FACTS Analyser 2.0* and *OPTIMISE Browser 2.0*. Figure 4 below shows the visualization of optimized data for the VCC case study as well as how an engineer uses the visualization in practice through OPTIMISE Browser 2.0. Through the research of the SBI algorithm, we have developed a reference point based technique to drive the innovization process towards the preference region(s) selected by the decision maker. This new technique is an outcome that had not been expected but turned out to be a very promising idea as the decision maker can be involved to drive both the optimization as well as the innovization process to extract the knowledge and speed-up the optimization process.

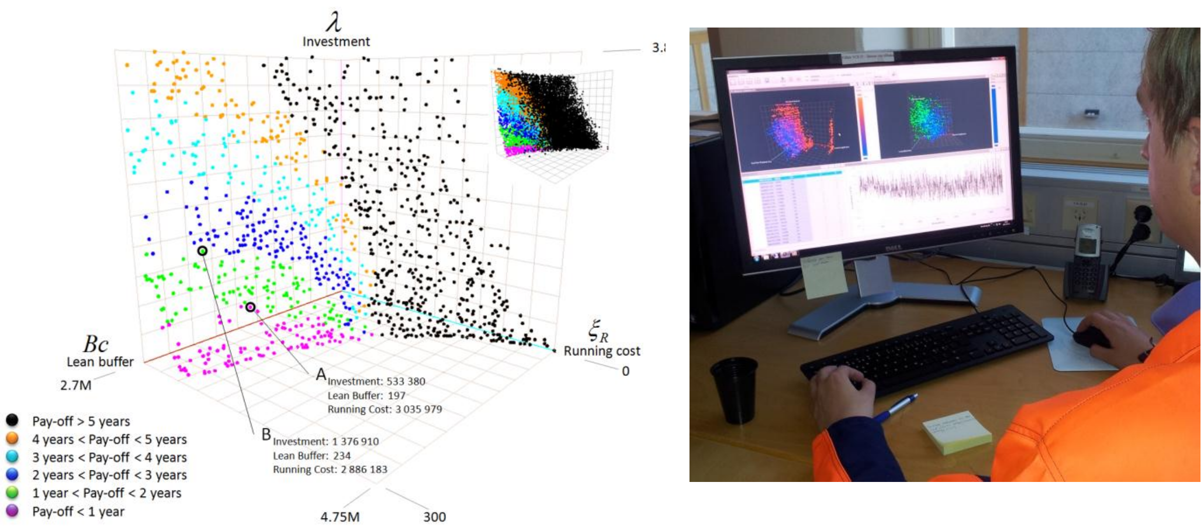

Figure 5. Results from VCC’s cost optimization case study and OPTIMISE Brower 2.0.

The exploration of a completely new automatic bottleneck and improvement potentials analysis algorithm, SCORE, is another outstanding outcome which had not been expected when the HSO project started. Based upon the concept of Innovization, SCORE is a novel method because unlike ordinary bottleneck detection methods, it not only tells where is the constraint (bottleneck) located, but also effectively indicating what should be the improvement(s) to remove the constraint. Such a powerful algorithm has been tested and verified with the model developed for a cylinder head machining line in one of the business case studies.

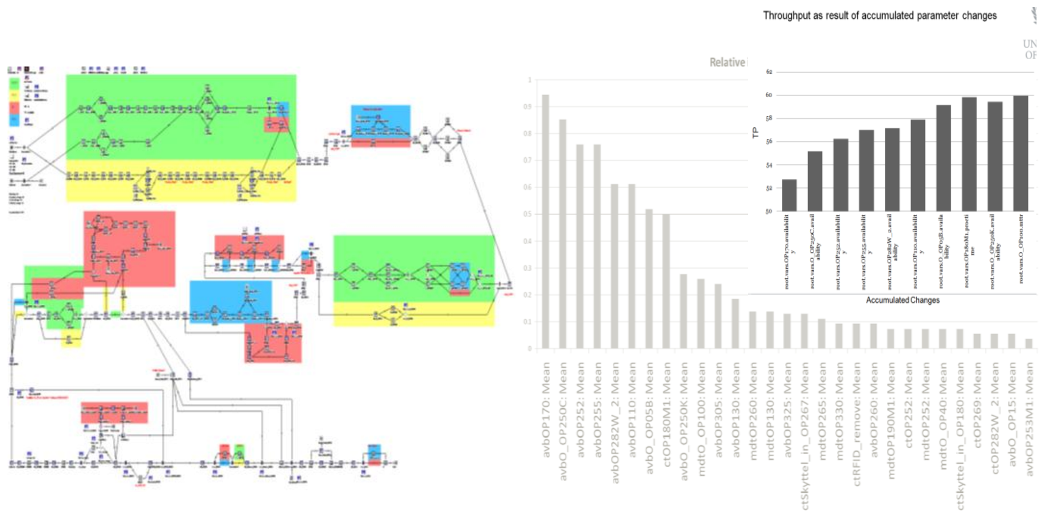

Figure 6. The SCORE method tested on a cylinder head machining line.

5.1 Delivery to FFI-goals

In general, the HSO project shares the same vision of the FFI strategic roadmap that the rapid development of virtual tools and applications of virtual manufacturing engineering as early as possible in the product/production development lifecycle, are the crucial areas for the creation of innovative and sustainable products. In the following, we highlight how the results delivered by have addressed some of the targets of FFI:

- The potential of over 30% higher productivity in production processes, which has been verified and demonstrated in the VCC business case studies. A strong competitiveness helps to ensure the production of components and vehicles in Sweden, which also secures the long-term product development in Sweden.
- 10-15% general improvement in energy efficiency can be achieved. Again this has been verified in the case study with VCC and Scania when SMO was applied to find more efficient production solutions that require less resources as well as finding optimal setting that can achieve the same production capacity with less energy consumption respectively.
- The innovative applications of virtual manufacturing engineering tools explore in HSO has demonstrated a potential of over 30% higher productivity in manufacturing preparation. In other words, the time of production systems design, and therefore "time to market", can be significantly reduced.
- The HSO methodology and developed toolset can be used to seek the most efficient production logistic processes and flows, which can facilitate the production systems to be able to handle a mixture of different models and different powertrains, i.e. a sharp increase in the number of variants.

- The target to “analyse and optimize machine systems to identify hidden potentials and minimize risks for problems”, stated in the FFI strategic roadmap for 2015, can be partially addressed by the development of SCORE.
- FACTS Analyzer and other HSO results are being used in industrial education, currently in the PSU course offered by the University of Skövde. This has introduced an important step to address the issue that Swedish industry demands more skilled personnel with adequate training in production engineering, production systems flow and strategies in general and the use of IT solutions, including virtual systems and methods (simulation of systems and processes) in specific.

Dissemination and publications

6.1 Knowledge and results dissemination

Academic publications and industrial educations are the two main channels that the knowledge and results generated from the HSO project are disseminated, not only during the project period but are still on-going continuously. In terms of scientific contributions, altogether there are over 32 scientific articles produced during the project period, wherein 10 of them are published or submitted (5 under review) to international peer-reviewed journals. There are 18 conference papers published in high-ranked conferences within optimization (e.g. CEC & LION). We may also conclude that both Swedish and International researchers have showed their recognition of the innovization concept introduced in HSO, because two of our recent conference publications have received the best paper award (SPS’12 and LION7; see Section 6.2). The publication work will continue even after the project is completed. At the time of writing, we are preparing two papers to the Industrial Simulation Conference (ISC) 2013 as well as a journal draft aiming at the Journal of Advanced Engineering Informatics.

As mentioned previously, industrial workshops and courses are probably the most effective form to disseminate research results to industry. The course Production System Development (7.5 ECTS), was started in 2011 as one of the key spin-off of the HSO project. The course was originally proposed by Volvo Car targeted to equip their production engineers/technicians with the scientific knowledge and best practices in designing and improving production systems in general. In the current course plan, there is a one-day workshop on SMO, as well as a one-day workshop on using the HSO toolset and results for teaching some important production system development concepts. This approach of education is believed to be unique and effective, as reflected by the 200+ engineers from VCC who received the education since 2011. Started from 2013, this course will be opened for different industrial companies.

6.2 Publications

The complete publication list of HSO can be found in the separate document on technical presentation; the following list provides some of the representative articles produced from the project:

Ng. A.H.C., Deb, K. and Dudas C. (2009). Simulation-based Innovization for production systems improvement: an industrial case study. In *Proceedings of the 3'rd Swedish Production Symposium (SPS'09)*, Gothenburg, Sweden, 2-3 December 2009. **(The first publication that introduces the SBI concept)**

Dudas, C., Frantzén, M., Ng, A.H.C. (2011). A synergy of multi-objective optimization and data mining for the analysis of a flexible flow shop. *Journal of Robotics and Computer Integrated Manufacturing*. Volume 27, Issue 4, pp. 687-695. **(The first journal publication that introduces the combination of SMO and data mining)**

Ng, A.H.C., Svensson, J. and Syberfeldt, A. (2012). A comparative study of production control mechanisms using simulation-based multi-objective optimization. *International Journal of Production Research*, Vol. 50, Issue 2, pp. 359-377. **(The first publication that introduces the use of SMO for comparing different production control strategies)**

Pehrsson, L., Ng, A.H.C. and Bernedixen, J. (2011). Multi-objective production system optimisation including investment and running costs. In *Evolutionary Multi-objective Optimization in Product Design and Manufacturing*, L. Wang, A. Ng, K. Deb (eds), Springer, 431-454. **(Documentation of the VCC cost optimization case study)**

Pehrsson, L., Ng, A.H.C. and Bernedixen, J. Automatic identification of bottleneck and potential improvements using multi-objective optimization and post-optimality analysis, submitted to *Omega: The International Journal of Management Science.* **(The first publication in SCORE)**

Siegmund, F., Ng, A.H.C., Bernedixen, J., Pehrsson, L. and Deb, K. (2012). Reference Point-based Evolutionary Multi-objective Optimization for Industrial Systems Simulation, Winter Simulation Conference 2012, Berlin, Germany. **(Documentation of finding optimal improvement actions in the cylinder block machining line at VCC)**

Ng. A.H.C., Dudas, C., Pehrsson, L. and Deb, K. (2012). Knowledge Discovery in Production Simulation by Interleaving Multi-Objective Optimization and Data Mining. In *Proceedings of the 5'th Swedish Production Symposium (SPS'12)*, Linköping, Sweden, 6-8 November 2012, 461-471. **(Best paper award in Industrial Automation)**

Hossain, M., Harari, N., Semere, D., Mårtensson, P., Ng, A.H.C. and Andersson, M. (2012). Integrated Modeling and Application of Standardized Data Schema. In Proceedings of the 5'th Swedish Production Symposium (SPS'12), Linköping, Sweden, 6-8 November 2012. **(Documentation of the model developed for the Scania case study)**

Ng. A.H.C., Dudas, C., Boström, H. and Deb, K. (2013). Interleaving Innovization and Multi-Objective Decision-Making for Faster Convergence in Production Systems Optimization. The 7th International Conference on Learning in Intelligent OptimizatioN (LION7), 7-11 January, 2013, Catania, Italy. **(Best long paper award)**

Conclusions and future research

Started from an early stage of the HSO project, important results in cost and sustainability optimization had been generated together with VCC. Later the HSO concepts and partially developed HSO toolset had been tested with Volvo AB and Scania and applied to their industrial problems. In all these case studies, our partner Swerea SWECAST has contributed significantly in energy consumption measurement and data analysis. Apart from aiding the simulation modeling for Scania, our partner at Royal Institute of Technology (KTH) has also developed a unique set to model energy consumption which can be effectively embedded into a discrete-event simulation model. It can be concluded that the FFI-HSO project consortium has achieved significant progresses throughout the entire project period, thanks to the following three major factors:

1. The clear, well-defined and unified objectives of the project that are interested by all partners in the consortium.
2. The close collaborations between the academic/research institutions and industrial partners within the consortium.
3. FACTS Analyzer and the Internet-enabled simulation optimization platform, developed in previous research projects at the University of Skövde, have provided the solid knowledge foundation and generic computing platform for the business case studies so that results can be generated quickly at an early stage.

While there have been scientific breakthroughs, in terms of the development of the SBI and SCORE algorithms, as well as significant industrial values, in terms of cost and sustainability optimization, generated in the project, we very well recognize that there are some outstanding scientific issues that need to be tackled in the coming future. But in order to “convert our research more quickly into practical applications” and our research outcomes to the hands of frontline production managers/engineers, there is a need to continue the HSO efforts to complete an highly innovative and interactive toolset for their daily uses for optimal continuous improvement and decision making. The research team is planning to continue in such a research direction both within and outside the FFI program.

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