DECISION SUPPORT AND SIMULATION METHODS FOR ASSEMBLY SYSTEM SALES ENGINEERS

Juhani Heilala[1], Otso Väätäinen[1], Jari Montonen[1], Harri Kulmala[2,] Toni Laaksonen[3]

[1,2]VTT Technical Research Centre of Finland
[1]P.O.Box 1000, FI-02044 VTT, FINLAND
[2]P.O.Box 1300, FI-33101 TAMPERE, FINLAND
[3]ABB Oy Service, P.O.Box 116, FI-00381 HELSINKI, FINLAND

juhani.heilala@vtt.fi (Juhani Heilala)

Abstract

This article presents decision-support methods and tools for assembly system sales engineers using 3D visualisation, component-based simulation, other equipment efficiency analysis and novel cost analysis methodology. The objective of modern assembly processes is to produce high-quality, low-cost products. To ensure that an assembly system is appropriately designed, system measurement schemes should be established for determining and understanding design effectiveness. Measurements can be classed in two categories: cost and performance. Understanding manufacturing costs is the first step toward increasing profits. The authors have developed an analysis method that integrates factory simulation, Overall Equipment Efficiency (OEE), and economic analysis methods. Advanced cost calculation includes Cost of Ownership (COO), commonly used investment evaluation methods, discounted cash flow techniques, Net Present Value (NPV) and Internal Rate of Return (IRR). The idea is to integrate these methods with simulation analysis to be used in the assembly system sales process. These methods can also be used to improve the design of flexible, modular reconfigurable assembly systems. The development of the Total Cost of Ownership (TCO) analysis tool is based on industrial standards and the authors' own experience in modular assembly system design, economic analysis and production simulation. The TCO methodology is useful in system supplier and end-user communication and helps in trade-off analysis of the system concepts.

Keywords: Decision support, component based simulation, system performance, economic and life cycle analysis

Presenting Author's biography

Juhani Heilala is a senior research scientist at VTT, the Technical Research Centre of Finland, with 20 years of experience in industrial robotics, production system development and various simulation techniques. The current research interest includes expanding simulation and modelling from system design and analysis methods to simulation based manufacturing operation planning and integration of production system simulation with other analysis methods.

ISBN 978-3-901608-32-2

1 Introduction

This article presents a decision support system designed especially for system sales engineers (Fig. 1). Ideally it could be used by the system end-user, the customer, the systems integrator and the sales engineer. The presented approach is based on component-based simulation, system visualisation, calculation and analysis of key performance indicators (KPI) and advanced cost analysis methodology.

The objective of modern assembly processes is to produce high-quality, low-cost products. To ensure that an assembly system is appropriately designed, system measurements should be established to provide understanding of design effectiveness. Measurements can be classified in one of two categories: cost and performance [1]. Understanding manufacturing costs is the first step toward increasing profits. Throughput, utilisation, and cycle time continue to be emphasised as key performance parameters for existing operations and for the planning of new assembly systems, but the cost issues need to be analysed also, as early as possible in the system design phase. The purchase cost of the system is just one parameter to consider in performing a cost of ownership analysis. Operating cost, other variable costs, throughput of the system, yield and scrap cost, and the useful life of the system are other factors affecting the cost efficiency of the system.

2 Methods

There are many methods for decision support in selecting a production system: strategic approaches, analytic approaches, value analysis, mathematical analysis, experimental analysis and economic approaches. A list of potential justification methods is presented in Fig. 2. Strategic approaches are beyond the scope of this paper. The focus is on experimental analysis using discrete event simulation, value analysis using Overall Equipment Efficiency (OEE) analysis, some other mathematical analysis and economic analysis based on Cost of Ownership (COO) and discount cash flow methods, Net Present Value (NPV) and Internal Rate of Return (IRR). Some other capital budgeting methods are merely listed in the text.

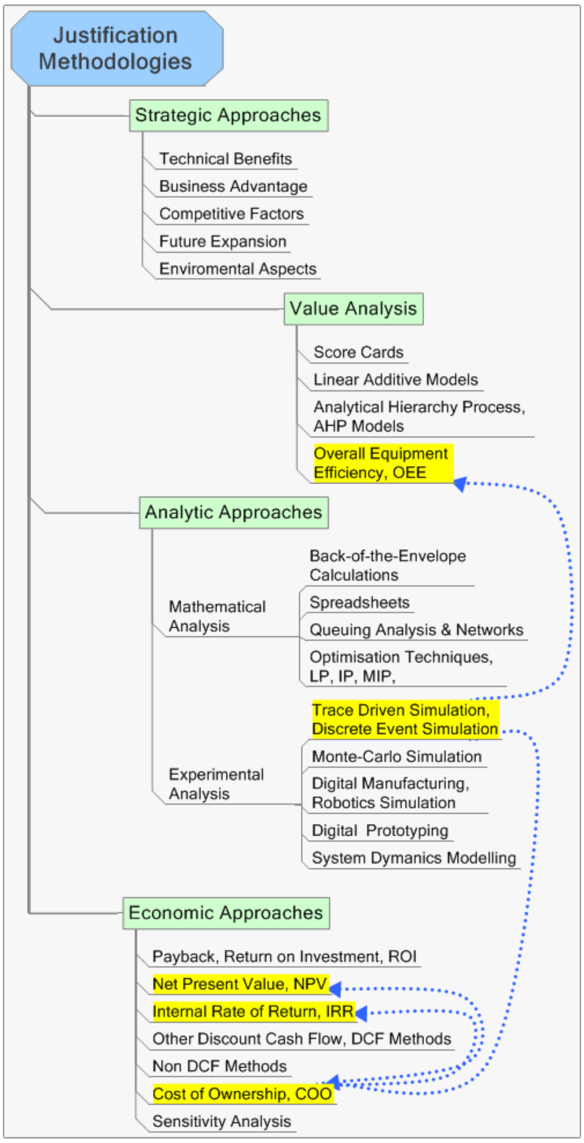

Fig. 2. Justification methods, inspired by Wiktorsson [2]

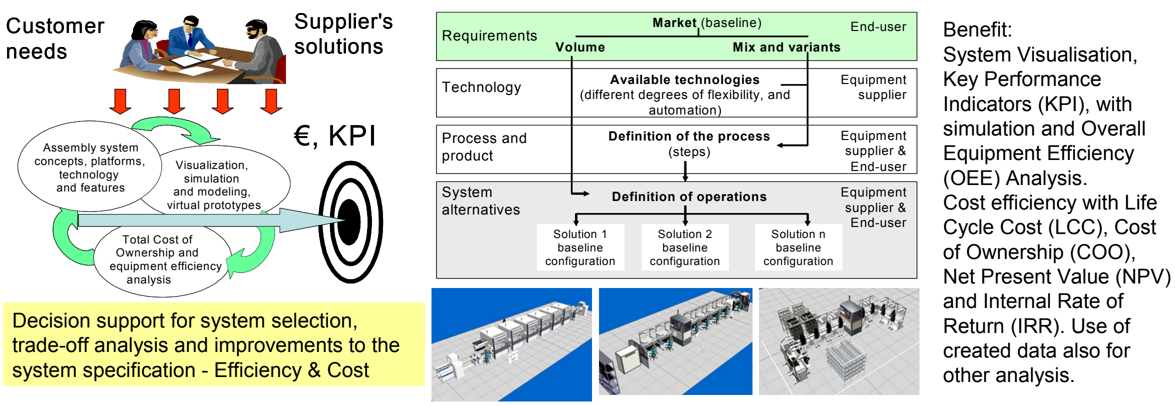

Fig. 1. Intended use of the VTT TCO Analysis Toolkit, MS2Value decision support method

2.1 Decision support

The authors have developed a decision support system for assembly system sales engineers. Decision Support Systems (DSS) are interactive computer-based systems intended to help decision-makers use data and models to identify and solve problems and to make decisions. The DSS framework has five major categories [3]:

- Communications-driven
- Data-driven
- Document-driven
- Knowledge-driven
- Model-driven DSS

The following chapters present the theories used in the development. A longer list of potential methods is given in Fig 2. There are many relations between the methods that are not shown here.

2.2 Simulation

Manufacturing systems, processes and data are growing and becoming more complex. Manufacturing, engineering and production management decisions involve the consideration of many interdependent factors and variables. These often complex, interdependent factors and variables are too numerous for the human mind to cope with at one time; therefore simulation modelling could help. Discrete event/material flow/factory simulation is commonly used in the manufacturing system design phase to evaluate concepts and optimise system solutions, sometimes also by training operators or selling ideas to potential customers, using a "virtual factory".

Reconfigurable and modular solutions for final assembly systems need equally modular design tools. Each modular building block of the real system needs to have a digital component for use in simulation model building, reconfiguration and analysis. Earlier development of simulation tools supporting modular production system design was presented by Heilala and Montonen in 1998 [4].

Component-based simulation software with 3D capabilities is ideal for the design and configuration of modular reconfigurable systems. The simulation platform should support discrete events analysis, like material flow, machine and also robotics simulation. There is at least one commercial software that has these features on a single platform (3Dreate® and 3DRealize®, [5]). Many manufacturing simulation tools are available on the market with different features. Many of the commercial tools are suitable for production system design evaluation and support sub-model merging; thus simulation library models can be created. The authors' latest development was based on a commercial 3D simulation tool shown in Figs. 3 and 4.

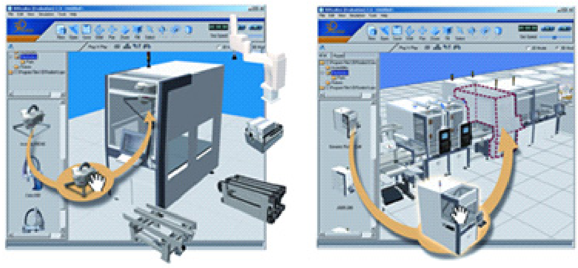

Fig. 3. Component based simulation supports modular system design [5]

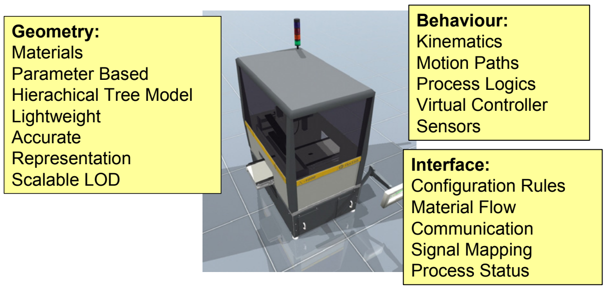

Fig. 4. Simulation component features

The simulation component shown in Fig. 4 is an image of real world equipment with geometry, behaviour and interface definitions. These components have a high re-use value but they do change the model building process. The design of a modular production system is like selecting suitable modules from an e-catalogue and placing them in the right order to achieve the correct process flow and system layout. This really speeds up the design and evaluation process, if the needed simulation components and data are available.

The other advantage of using 3D simulation is visualisation of the system, which improves communication. The end-user and system integrator can configure the virtual system during the sales meeting and evaluate the customer's future needs, since modifying the simulation model is a rapid process. However, this does require some homework before the meeting.

Simulation analysis provides many performance indicators. The common aim is to identify problem areas, and quantify or optimise production system performance such as:

- Throughput under average and peak loads
- Utilisation of resources, labour and machine, staffing requirements, work shifts
- Bottlenecks and choke points, queuing at work locations, queuing and delays caused by material handling devices and systems
- Effectiveness of the scheduling system, routing of material, WIP and storage needs

There are many excellent textbooks on simulation [6, 7, 8, 9] that provide guidelines for simulation projects, model validation and verification and simulation analysis. These issues are not covered here.

2.3 OEE

Overall Equipment Efficiency, (OEE) is a performance evaluation method. Analysis is normally used for running system performance analysis. Practically it is more suitable for machine level analysis; on the production line we first need to find a bottle-neck machine that can perform the OEE analysis. Development efforts to expand OEE to production line and factory level are ongoing [10].

OEE is an all-inclusive metric of equipment productivity. It is based on time analysis and classification of reliability (MTBF), maintainability (MTTR), utilisation (availability), throughput, and yield (see Fig. 5).

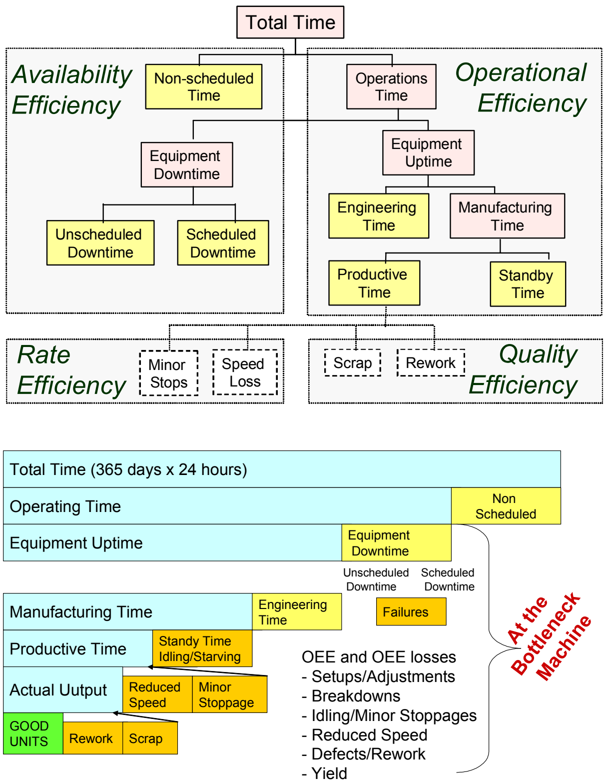

Fig. 5. OEE, from total time to number of good units.

All the above factors are grouped into the following three sub-metrics of equipment efficiency. The three sub-metrics and OEE are mathematically related as follows [11, 12]:

OEE, % = Availability Efficiency x Performance Efficiency x Quality Efficiency x 100%

Definition of sub-metrics:

1. ***Availability Efficiency***: The fraction of total time that the equipment is in a condition to perform its intended function = (Equipment Uptime)/(Total Time)

2. ***Performance Efficiency***: The fraction of equipment uptime during which the equipment is processing actual units at theoretically efficient rates = (Operational Efficiency) x (Rate Efficiency).

- Operational Efficiency - The fraction of equipment uptime during which the equipment is processing actual units = (Production Time)/(Equipment Uptime).

- Rate Efficiency - The fraction of production time during which the equipment is processing actual units at theoretically efficient rates = (Theoretical Production Time for Actual Units)/(Production Time)

3. ***Quality Efficiency:*** The theoretical production time for effective units divided by the theoretical production time for actual units.

- Effective Units = (Actual Units) - (Scrap Units + Rework Units)

In the system design phase, OEE analysis is a systematic way to analyse system performance and also calculate the number of good products produced. OEE provides a systematic way to classify and study equipment efficiency and time related losses. It helps to identify the actual time the system is producing good units. OEE can be used for evaluating different production work time and work shift arrangements and at the same time identify and evaluate the OEE losses shown in Fig. 5. This is useful if both the system vendor and the customer feed the information together and create a common understanding of system performance. Later, the same metrics can be used for monitoring the real system.

The OEE analysis used by the authors is based on semiconductor industry standards SEMI E10, E79 [11, 12] now applied to another industrial branch. Simulation and OEE type analysis can be integrated as shown elsewhere [13]. Simulation run results can be shown using OEE methodology, since the simulation model can provide the same information as a real system.

2.4 LCC

Life cycle costs (LCC) are summations of estimated cost from inception to disposal for both equipment and projects. LCC methodology is commonly used in the process industry, and also often applied to energy technologies and building projects. LCC can be applied to other types of application; there is no limit to the use of the method.

The objective of LCC analysis is to choose the most cost effective approach from a series of alternatives so the least long-term cost of ownership is achieved while considering cost elements which include design, development, production, operation, maintenance, support, and final disposition of a major system over its anticipated useful life span [14]. LCC analysis is also covered in COO calculations (see Chapter 2.6). The LCC method normally uses discount cash flow methods, if the income can be estimated. NPV and IRR are discussed in Chapter 2.7.

2.5 TCO for information technology

Originally, Total Cost of Ownership (TCO) modelling was a tool that systematically accounted for all costs related to an IT (Information Technology) investment decision. TCO models were initially developed by Gartner Research in 1987 and are now widely accepted. Simply stated, TCO includes all costs, direct and indirect, incurred throughout the life cycle of an asset, including acquisition and procurement, operations and maintenance, and end-of-life management.

A similar TCO concept is also widely used in the automobile industry. In this context, the TCO denotes the cost of owning a vehicle from its purchase, through its maintenance, to its sale as a used car. Comparative TCO studies between various models help consumers choose a car to fit their needs and budget. The TCO methodology can be used for vendor selection and sourcing evaluation [15, 16, 17].

2.6 Standardised COO

Cost of Ownership (COO) is a semiconductor industry metric to evaluate the unit cost effectiveness of semiconductor equipment based on standard SEMI E35 [18]. COO was originally developed to address the economic and productive performance of a wafer fabrication tool by estimating the total life-cycle cost of a specific process step [19]. The standardised method has become a common reference between equipment suppliers and equipment users in the semiconductor industry. There are dedicated commercial tools on the market [20]. COO methodology has also been used in optoelectronic factory automation evaluation [21]. The difference from LCC or traditional TCO is that SEMI COO evaluates all the life cycle costs, including cost of bad quality and rework, and shows the results also as unit cost of acceptable assemblies.

The basics of COO is simple: all the costs during the system life-cycle are divided by the number of good units produced [18, 21]. Thus COO depends on the production throughput rate, equipment acquisition cost, equipment reliability, throughput yield, and equipment utilisation. The idea is to calculate unit cost. The basic COO is given by the following equation:

COO per unit = all costs/number of good products

$$COO = \frac{FC + VC + YC}{L * THP * Y * U} \qquad (1)$$

Where:

FC = Fixed costs (amortised for the period under consideration), purchase, installation, training, …

VC = Operating costs (variable or recurring costs, labour costs), maintenance, materials, …

YC = Yield loss costs

L = Lifetime of equipment

THP = Throughput rate

Y = Yield

U = Utilisation

Throughput, yield, reliability and equipment utilisation can be analysed with a simulation model or OEE calculation model. The most difficult issue is getting proper data for analysis.

2.7 Discount Cash Flow methods

A production system is an investment project, and there is also a need for capital budgeting analysis. Some of the suitable methods are listed here. The most used discount cash flow analysis methods are Net Present Value (NPV) and Internal Rate of Return (IRR). The other cash flow techniques are: the Modified Internal Rate of Return method (MIRR), Real Options methods (RO) and the Equivalent Annuity method (EA). Techniques based on accounting earnings and accounting rules are: Accounting Rate of Return (ARR) and Return on Investment (ROI). Simplified and hybrid methods are: payback period and discounted payback period.

Net Present Value (NPV) is an important economic measure for projects or equipment taking into account discount factors and cash flow. Using the NPV method, a potential investment project should be undertaken if the present value of all cash inflows minus the present value of all cash outflows (which equals the net present value) is greater than zero.

$$NPV = \sum_{t=1}^{N} \frac{C_t}{(1+r)^t} - C_0 \qquad (2)$$

Where:

t = the time of the cash flow

N = the total time of the project

r = the discount rate

C_t = the net cash flow (the amount of cash) at time t

C_0 = the capital outlay at the beginning of the investment time (t = 0)

A key input is the interest rate or “discount rate” which is used to discount future cash flows to their present values. If the discount rate is equal to the shareholder’s required rate of return, any NPV > 0 means that the required return has been exceeded. The project with the greatest NPV is usually the winner.

The Internal Rate of Return (IRR) is defined as the discount rate that gives a net present value (NPV) of zero. The IRR method will result in the same decision as the NPV method for independent (non-mutually exclusive) projects, in the usual cases where a negative cash flow occurs at the start of the project, followed by all positive cash flows. In the most realistic cases, all independent projects that have an IRR higher than the hurdle rate should be accepted.

Production system purchase is an investment, and it is a project the profitability of which needs to be evaluated. The literature shows how to use NPV [22] and IRR [23] in project comparison. There is a need to use both NPV and IRR methods, since they can give different final results, even from the same data [24]. For example, depending on the size of the investment, a big investment can have higher ranking with NPV evaluation, whereas the IRR evaluation ranking remains small. NPV is theoretically stronger and IRR is well suited for cyclic investment.

2.8 Other investment evaluation

Return on Investment (ROI) is also a performance measure used to evaluate the efficiency of an investment or to compare the efficiency of a number of different investments. To calculate ROI, the benefit (return) of an investment is divided by the cost of the investment. The result is expressed as a percentage or a ratio. ROI is a very popular metric because of its versatility and simplicity.

Payback Period: the length of time required to recover the cost of an investment. All other things being equal, the better investment is the one with the shorter payback period. For example, if a project cost $100,000 and was expected to return $20,000 annually, the payback period would be $100,000 / $20,000, or 5 years. There are two main problems with the payback period method: 1) It ignores any benefits that occur after the payback period and, therefore, does not measure profitability; 2) it ignores the time value of money.

For these reasons, other methods of capital budgeting like NPV, IRR or other discounted cash flow are generally preferred.

3 Integration of methods

The novelty here is in the integration of methods. Earlier development steps have been presented elsewhere [25-30]. Now that new features are being developed, discount cash flow techniques like NPV and IRR will be included. The decision support methods comprise the VTT TCO Analysis toolkit (see Fig. 6).

Integration methods are being improved in the latest version. The authors are also aiming to use a different simulation software version. Instead of 3DCreate® as shown in the earlier development, they are hoping to use 3DRealize®. More details about the software are available on the vendor web site [5].

In the current prototype tool, the authors have integrated component-based simulation with an MS Excel analysis workbook. Developers are using a COM interface, Python scripts, and Excel-internal links.

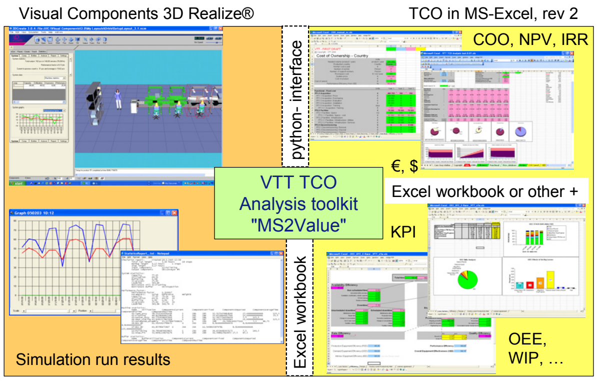

Fig. 6. Integration of methods

3.1 Hybrid method integration

A hybrid simulation and analytic model is a mathematical model that combines identifiable simulation and analytic models; this is clearly the case in the development presented.

An analytic model is a set of equations that characterises a system or a problem entity, and a simulation model is a dynamic or an operating model of a system or problem entity that mimics the operating behaviour of the system or problem entity. The analytic model tends to provide exact and static information, while the simulation model provides approximate and dynamic information about the system of interest or problem entity [31].

Hybrid simulation and analytic models can be classified into the following six categories, the first five of which are presented elsewhere [31] (see Fig. 7):

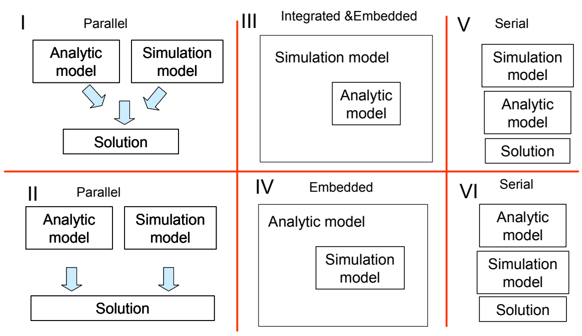

Fig. 7. Hybrid methods

Class I: A model whose behaviour over time is obtained by alternating between independent simulation and analytic models.

Class II: A model where a simulation model and an analytic model operate in parallel over time with interactions through their solution procedures.

Class III: A model where a simulation model is used in a subordinate way for an analytic model of the total system.

Class IV: A model where a simulation model is used as an overall model of the total system and requires analytic solutions as input parameters from the analytic models.

Class V: A model where simulation output is used as input to an analytic model.

Class VI: A model where analytic output is used as input to a simulation model.

The hybrid method presented here is basically Class I. The independent static analytical analysis, OEE, COO, NPV and IRR calculation is used parallel to discrete event simulation. It can also be used in serial, Class V type simulation runs; the results are used for OEE and COO analysis. In the integrated version it is like Class III, since using simulation software interface engineers are able to manipulate some analytical calculations.

4 VTT TCO Analysis toolkit

The solution concept presented here is a hybrid DSS solution. The user uses complex multi-criteria models to provide decision support. The solutions use data and parameters provided by decision-makers to help analyse the suitability of production line concepts and to compare different solutions. The system can be called model-oriented or model-based decision support systems and the simulation model is an essential part.

Development is ongoing, and currently a functional prototype is being validated and debugged. The current most advanced development phase is shown in Fig. 8.

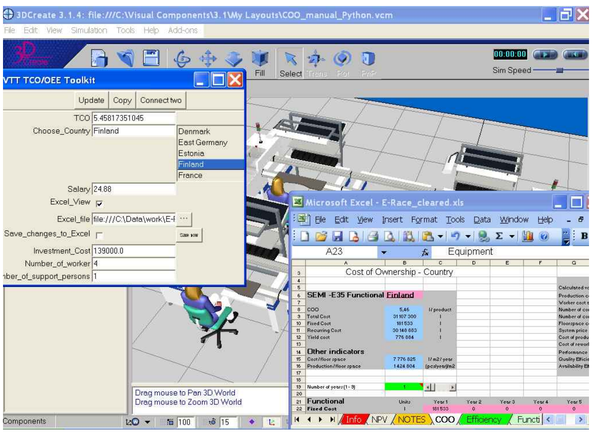

Fig. 8 Integration of simulation and mathematical analysis in Excel format

4.1 Use of the VTT decision support system

Integration of the different methods presented in the previous chapters has resulted in VTT TCO Analysis toolkit methodology. In the methodology, component based simulation is used for layout visualisation, system configuration and production simulation analysis, like finding bottleneck machines, line balance and system throughput studies. OEE analysis shows loss factors and productive time. The OEE and simulation studies are partially overlap. COO calculates different cost issues, unit cost and life cycle costs. Finally capital budgeting methods, NPV and IRR are also used to present data for decision making.

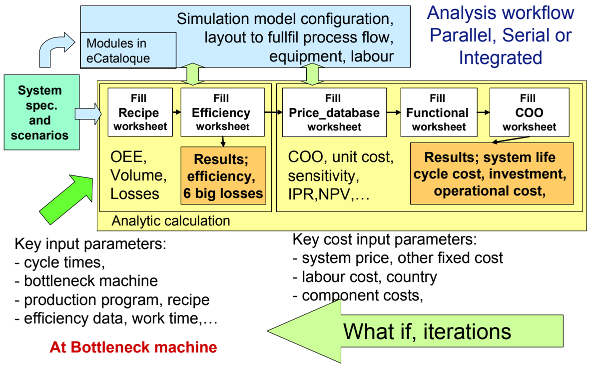

Fig. 9. Analysis workflow

There are several steps in the analysis workflow and it is an iterative process (see Fig. 9). Simulation model configuration and assembly system layout design starts the definition of some cost issues. Each simulation component added to the model increases the purchase price function, and, similarly, every added human operator to the model increases the labour cost function. The selection of country sets country-specific salary data. Other data is either given by default values or the user may enter data manually in the specific places in the Excel workbook.

In the most advanced existing prototype, the model builder sees interactively the effects of his or her selection in the simulation software user interface (see Fig. 8). Most of the data is stored in the Excel sheets and the simulation model can read and write the specific cells. Internal links and macros in the Excel workbook update the data for calculations. Some of the data used for analysis are default values, which are user editable.

The TCO Analysis Toolkit Excel workbook can also be used without the simulation as an independent analysis tool, while the user is entering all the necessary data manually.

There are many parameters to study before evaluating the assembly systems baseline solution or comparing with other system configurations:

- Different baseline solutions, degree of automation, factory location (salary)

- Bottleneck, capacity & utilisation analysis, OEE calculation (availability, performance, quality), identification of OEE and other losses
- Economic analysis, COO, NPV, IRR
- Scenario comparison, same baseline, variations in work time, quality, efficiency, …
- Life-cycle scenarios - modifications - upgrades
- Risk management (min - max), sensitivity

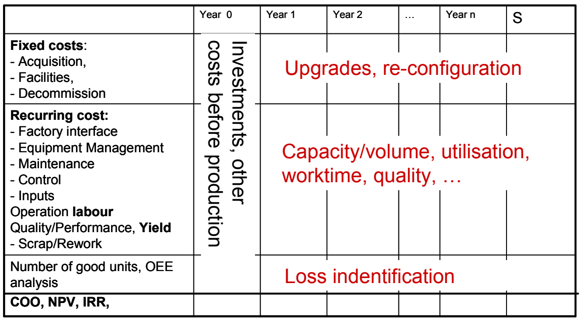

Fig. 10. Analysis covers the system life-cycle

The system life cycle can be analysed as shown in Fig. 10. As a default, many parameters are linear or fixed, but by entering additional data in the proper places on the Excel worksheet, also equipment upgrades and volume fluctuation can be analysed. There are really a lot of other factors and parameters that could be entered into the calculation, but are currently not used automatically. For example, studies on flexibility, system re-configuration and incremental investment need a lot of manual interaction.

4.2 Illustrative examples with a fictitious case study

Some earlier fictitious case studies without the latest development in NPV and IRR analysis are discussed elsewhere [25-30]. An earlier example of use of the methodology covers assembly line concept comparison, as well as system life cycle analysis. Pending debugging and methodology validation, new case studies with the latest developments are not yet available.

5 Discussion

This paper presents a hybrid decision support system for assembly system sales engineers. Different methods have been integrated to aid engineers in the design and sales of a modular reconfigurable final assembly system. The sales engineer can justify the solutions using simulation, efficiency analysis, unit cost, and system life cycle cost and discount cash flow analysis methodology. The theory behind the analysis is also briefly explained. The developed VTT TCO Analysis toolkit is a prototype and current proof of the concept. The calculation engine in Excel can partly be used alone without simulation modelling.

Cost of Ownership (COO) provides an objective analysis method for evaluating decisions. COO provides an estimate of the life-cycle costs (LCC). The analysis highlights details that might be overlooked, thus reducing decision risk. COO can also be used for evaluation of processing and design decisions. Finally, COO allows communication between suppliers and users. They are able to speak the same language, comparing similar data and costs using the same analysis methods. Both suppliers and manufacturers can work from verifiable data to support a purchase or implementation plan. There is also a need for investment calculation methods, discount cash flow methods, NPV and IRR. These methods are especially important for upper management decision making.

The lifetime cost of ownership per manufactured unit is generally sensitive to production throughput rates, overall reliability, and yield. In many cases, it is relatively insensitive to initial purchase price. With correct parameters an engineer can justify investments in flexibility and automated equipment, or at least determine threshold values.

Overall Equipment Efficiency (OEE) is usually a measurement of single-machine performance. Here the calculations are used for a bottleneck machine, and in practice the Overall Throughput Efficiency of the assembly line is calculated. With a serial line and single product, this can be quite simple. The analysis is more complex with mixed production and layout with parallel operations. Simulation studies can pinpoint bottleneck equipment. One of the limitations of OEE analysis is that the analysis is process or equipment-centric and the material flow or work in process (WIP) is not analysed, another reason to use factory simulation.

The authors believe that COO and OEE are becoming increasingly important in high-tech decision-making processes. Capital budgeting analysis and discount cash flow analysis are always important, since money (€ or $) is a very strong measure of a successful project. There is also a need to increase the acceptance of simulation within industry. Component-based simulation methods are on the right track, since they speed up modelling and thus also the analysis cycle.

Predicting the future is always difficult. An engineer can design a very cost-effective assembly system, but in real life will there be customer orders as planned, and will the planned life-cycle of system be as long as estimated before system re-configuration? Easy-to-use combined, hybrid and integrated methods with simulation modelling as shown here are a new way to define information and data for decision making. If analysis is easy to carry out, most likely engineers will analyse more scenarios. This is also needed for risk evaluation and sensitivity analysis.

Users should remember that, as with all simulation analysis, this kind of simulation is sensitive to input data, and that input of false information does not produce the right results. The real challenges are in getting data for analysis; to some extent, economics models need company-confidential data. Are end-users ready to share this data with system sales engineers? The challenge is also getting other correct data, and how to estimate yield and future production volumes. Knowing this, the authors are not aiming at absolute results in the design phase but, rather, at obtaining data for comparison of design alternatives. Later on, real factory data and accounting data can be used to verify the models and thus improve the results in the next evaluation round and new system designs.

6 Summary of the future

The intended use of the VTT decision support tool is in the sales process of modular, re-configurable assembly systems. Naturally, use of the toolkit can be expanded to other areas as well.

For future development, real case studies with industrial partners are in progress. The aims are to improve integration of the analysis into the component-based simulation software, and to obtain analysis data from simulation input data files and the results of simulation runs with minimum effort from users. The aim is a user-friendly system.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the financial support received from the Finnish Funding Agency for Technology and Innovation (TEKES), VTT and Finnish industry. The development was part of the MS2Value project [32].

7 References

[1] Chow (1990): We-Min Chow. Assembly Line Design, Methodology and Applications. Marcel Dekker, Inc., New York and Basel, 1990.

[2] Wiktorsson, M. Performance Assessment Of Assembly Systems: Linking Strategy To Analysis In Early Stage Design Of Large Assembly Systems. Doctoral Dissertation. Royal University of Technology, 2000.

[3] Power, D.J. A 2007 Brief History of Decision Support Systems. DSSResources.COM, www, http://DSSResources.COM/history/dsshistory.html, version 4.0, March 10, 2007.

[4] Heilala, Juhani; Montonen, Jari. 1998. Simulation-based design of modular assembly system - use of simulation module library. Eurosim Congress 1998, 3rd International Congress of the Federation of EUROpean SIMulation Societes. Espoo, FI, 14 - 15 April 1998. Espoo, VTT Automation. 6 p.

[5] www.visualcomponents.com, accessed 4th July, 2007.

[6] Law, A.M., Kelton, W.D. Simulation Modelling & Analysis. 2nd edition 1991.

[7] Banks, J;.Carson, J.S , Nelson, B.L. Discrete-Event System Simulation. 2nd Edition. Prentice Hall, 1996. ISBN 0-13-217449-9

[8] Banks J. (ed) 1998. Handbook of Simulation. Principles, Methodology, Advances, Applications, and Practice. John Wiley & Sons, Inc. 1998.

[9] Charles Harrell, Kerim Tumay. Simulation made easy. A manager's guide. Industrial Engineering and Management Press. Institute of Industrial Engineers. 1995. ISBN 0-89806-136-9.

[10] Richard Oechsner, Markus Pfeffer, Lothar Pfitzner, Harald Binder, Eckhard Müller, Thomas Vonderstrass. From overall equipment efficiency (OEE) to overall Fab effectiveness (OFE). Materials Science in Semiconductor Processing 5 (2003) pp 333–339.

[11] SEMI E10-0304, 2004, Specification for Definition and Measurement of Equipment Reliability, Availability, and Maintainability (RAM), SEMI International Standard, http://www.semi.org.

[12] SEMI E79-0304, 2004, Specification for Definition and Measurement of Equipment Productivity, SEMI International Standard, http://www.semi.org

[13]Huang, Samuel H., Dismukes, John P., Shi, J., Su, Qi, Razzak Mousalam A., Bodhale Rohit and Robinson D. Eugene . Manufacturing productivity improvement using effectiveness metrics and simulation analysis. International Journal of Production Research, 2003, Volume. 41, no. 3, 513–527

[14] Barringer, H. Paul and David P. Weber, 1996, "Life Cycle Cost Tutorial", Fifth International Conference on Process Plant Reliability October 2-4, 1996,, Gulf Publishing Company, Houston, TX, available from http://www.barringer1.com

[15] Degraeve, Z., Labro, E. and Roodhooft, F. An evaluation of vendor selection models from a total cost of ownership perspective. European Journal of Operational Research, Volume 125, Issue 1, 16 August 2000, Pages 34-58

[16] Degraeve, Z. and Roodhooft, F. (1999), Improving the efficiency of the purchasing process using total cost of ownership information: The case of heating electrodes at Cockerill Sambre S.A. European Journal of Operational

Research, Volume 112, Issue 1, 1 January 1999, Pages 42-53

[17] Wouters, Marc, Anderson James C. and Wynstra, Finn. (2005) The adoption of total cost of ownership for sourcing decisions-a structural equations analysis. Accounting, Organizations and Society, Volume 30, Issue 2, February 2005, Pages 167-191

[18] SEMI E35-0701, 2005, Cost of Ownership for Semiconductor Manufacturing Equipment Metrics, SEMI International Standard, http://www.semi.org.

[19] Dance, Daren L., DiFloria, Thomas, and Jimenez, David W. Modelling the Cost of Ownership of Assembly and Inspection. IEEE Transactions On Components, Packaging, And Manufacturing Technology-Part C, Volume. 19, NO. 1, January 1996. Pages 57-60.

[20] www.wwk.com, accessed 4th July, 2007

[21] Ragona Sid, Cost Of Ownership (COO) For Optoelectronic Manufacturing Equipment. 2002. Microsystems Conference. Rochester, N.Y, 200. available at http://documents.exfo.com/appnotes/anoteBurleigh002-ang.pdf

[22] Paul D. Gardiner and Kenneth Stewart: Revisiting the golden triangle of cost, time and quality: the role of NPV in project control, success and failure, International Journal of Project Management, Volume 18, Issue 4, August 2000, Pages 251-256

[23] Tung Au: The overall rate of return as a profit measure for capital projects, Engineering Costs and Production Economics, Volume 7, Issue 3, September 1983, Pages 235-241

[24] E. Borgonovo and L. Peccati: Uncertainty and global sensitivity analysis in the evaluation of investment projects, International Journal of Production Economics, Volume 104, Issue 1, November 2006, Pages 62-73

[25] Heilala, Juhani; Helin, Kaj; Montonen, Jari. Total cost of ownership analysis for modular final assembly systems. 18th International Conference on Production; Research, ICPR. 18. Salerno, 31 July - 4 Aug. 2005 (2005), 6 p.

[26] Heilala, Juhani; Helin, Kaj; Montonen, Jari; Voho, Paavo; Anttila, Mika. 2005. Integrating cost of ownership analysis into component-based simulation. CARV2005 Today's Reactions Tomorrow's Challenges. 1st Int. Conf. on Changeable, Agile, Reconfigurable and Virtual Production. Münich, 22 - 23 Sept. 2005. Technische Universität München, ss. 385 – 392

[27] Heilala, Juhani; Helin, Kaj; Montonen, Jari; Väätäinen, Otso. Life cycle and cost analysis for modular re-configurable final assembly systems. Precision Assembly technologies for Mini and Micro products. 3rd International Precision Assembly Seminar, IPAS'2006. Bad Hofgastein, Austria, 19 - 22 Febr. 2006. Ratchev, Svetan (Ed.). Springer (2006), 277 - 286

[28] Heilala, Juhani; Montonen, Jari; Helin, Kaj; Salonen, Tapio; Väätäinen, Otso. 2006. Life cycle and unit cost analysis for modular re-configurable flexible light assembly systems. Intelligent Production Machines and Systems. 2nd I*PROMS Virtual International Conference. 3 - 14 July 2006. Elsevier, ss. 395 – 400

[29] Heilala, Juhani; Helin, Kaj; Montonen, Jari. 2006. Total cost of ownership analysis for modular final assembly systems. International Journal of Production Research, vol. 44, 18 - 19, ss. 3967 - 3988

[30] Heilala, Juhani; Montonen, Jari; Helin, Kaj. Selecting the Right System - Assembly System Comparison with Total Cost of Ownership Methodology. Assembly Automation. Vol. 27 (2007) No 1. 44-54

[31] Sheng-Jen (Tony) Hsieh. Hybrid analytic and simulation models for assembly line design and production planning. Simulation Modelling Practice and Theory 10 (2002) 87–108.

[32] www.pe.tut.fi/MS2Value/index.html