



HAL
open science

18th ICPR paper: TOTAL COST OF OWNERSHIP ANALYSIS FOR MODULAR FINAL ASSEMBLY SYSTEMS

Juhani Heilala, Kaj Helin, Jari Montonen

► **To cite this version:**

Juhani Heilala, Kaj Helin, Jari Montonen. 18th ICPR paper: TOTAL COST OF OWNERSHIP ANALYSIS FOR MODULAR FINAL ASSEMBLY SYSTEMS. *International Journal of Production Research*, 2006, 44 (18-19), pp.3967-3988. <10.1080/00207540600806448>. <hal-00512925>

HAL Id: hal-00512925

<https://hal.science/hal-00512925v1>

Submitted on 1 Sep 2010

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



HAL Authorization



**18th ICPR paper: TOTAL COST OF OWNERSHIP ANALYSIS
FOR MODULAR FINAL ASSEMBLY SYSTEMS**

Journal:	<i>International Journal of Production Research</i>
Manuscript ID:	TPRS-2005-IJPR-0573.R1
Manuscript Type:	Original Manuscript
Date Submitted by the Author:	28-Apr-2006
Complete List of Authors:	Heilala, Juhani; VTT Technical Research Centre of Finland Helin, Kaj; VTT Technical Research Centre of Finland Montonen, Jari; VTT Technical Research Centre of Finland
Keywords:	ASSEMBLY SYSTEMS, DESIGN, COST ANALYSIS
Keywords (user):	efficiency analysis



TOTAL COST OF OWNERSHIP ANALYSIS FOR MODULAR FINAL ASSEMBLY SYSTEMS

J. Heilala[§]*, K. Helin[†] and J. Montonen*

*VTT Industrial Systems, P.O.Box 1000, FIN-02044 VTT, Finland

[†]VTT Industrial Systems, P.O.Box 1300, FIN-33101 Tampere, Finland

Correspondence *Juhani Heilala. email: juhani.heilala@vtt.fi

phone +358 20 722 5386, fax +358 20 722 7077

Abstract

The objective of modern assembly processes is to produce high-quality and low-cost products. Understanding manufacturing costs in the system design phase is the first step to increasing profits. Throughput, utilisation and cycle time continue to be emphasised as key performance indicators (KPI) for the planning of new assembly systems, but the cost issues need to be analysed as well. The authors are developing a novel analysis methodology that integrates component-based simulation, Overall Equipment Efficiency (OEE) with Cost of Ownership (COO) and other analysis methods to improve the design of flexible, modular re-configurable assembly systems. The development of the Total Cost of Ownership (TCO) analysis tool is based on selected industrial standards and the authors' own experience of assembly system design and simulation. The TCO method is useful in system-supplier and end-user communication and helps in trade-off analysis of system concepts. A fictitious case study illustrates the use of the TCO method.

Keywords: Assembly system design, cost and efficiency analysis

TOTAL COST OF OWNERSHIP ANALYSIS FOR MODULAR FINAL ASSEMBLY SYSTEMS

Abstract

The objective of modern assembly processes is to produce high-quality and low-cost products. Understanding manufacturing costs in the system design phase is the first step to increasing profits. Throughput, utilisation and cycle time continue to be emphasised as key performance indicators (KPI) for the planning of new assembly systems, but the cost issues need to be analysed as well. The authors are developing a novel analysis methodology that integrates component-based simulation, Overall Equipment Efficiency (OEE) with Cost of Ownership (COO) and other analysis methods to improve the design of flexible, modular re-configurable assembly systems. The development of the Total Cost of Ownership (TCO) analysis tool is based on selected industrial standards and the authors' own experience of assembly system design and simulation. The TCO method is useful in system-supplier and end-user communication and helps in trade-off analysis of system concepts. A fictitious case study illustrates the use of the TCO method.

Keywords: Assembly system design, cost and efficiency analysis

1. Introduction

The design of an assembly line or cell is an old problem but also a new one. New innovations in product and manufacturing technology often result in new design problems. On the one hand, technological advances lead to more sophisticated assembly systems; on the other, market competition causes shortened product lifetimes, which force a change or reduction in the service years of the assembly system. The assembly system design, therefore, plays an increasingly important role in manufacturing. The design work should be guided by a systematic approach, with careful evaluation of the design concept from both cost and performance viewpoints. A cost item usually measures the total amount of spending needed to produce a given number of products. This may include product design, development, laboratory testing, and all of the spending required to support production activity, such as direct and indirect labour, equipment, facilities and other overheads. The ratio of total spending to the total number of products is then the product unit cost [Chow 1990].

The ability to effectively identify cost drivers and manage cost reductions is a competitive advantage, and this should be done as early as possible in the assembly system concept evaluation and selection phase. Different cost estimation methods have been devised; a few of them measure intangible costs, such as flexibility, product yield, parts quality, process time variation, and so on. Although not all of these intangibles are easily understood, their costs may be measured by indirect methods. In many cases, a cost estimation method can be derived from performance measures. For example, flexibility would impact on the capital investment plan. Yield and quality are related to

1
2
3
4 capacity and material handling costs. Process time variation may cause problems with
5
6 workstation utilisation or in-process inventories [Chow 1990].
7
8
9

10
11 Final assembly systems in the electronics industry do have a modular structure. System
12 reconfiguration is needed in the current market climate, where system changes occur at
13 shorter and shorter intervals. The modular structure, the architecture of the assembly
14 system, has many advantages. It facilitates standardisation in that at least the selected
15 suppliers' modules are compatible and the system is scaleable. The system building
16 blocks can be divided into basic process platforms, exchangeable process modules and,
17 finally, product-related components; naturally, there are buffer modules and modules for
18 arranging the material flow. The design of the modular system is just like selecting the
19 suitable modules from a catalogue and placing them in the right order to get the correct
20 process flow and system layout. Modularity is a cost-efficient solution; it supports step-
21 by-step investment, and later upgrades or modifications to the system are also easier.
22 Standardised building blocks also help in calculating the cost of investment. Most of the
23 modules should be standard with known catalogue prices, thus product-related special
24 customisation is minimised.
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46

47 Simulation and virtual factory technology is commonly used for manufacturing system
48 design. Simulation studies can show the performance of the planned system and
49 different alternatives can be studied before the investment decision. Simulation software
50 with 3D visualisation capabilities does improve communication with different interest
51 groups. A modular system solution configuration can be greatly enhanced with the
52 proper design and evaluation tools, see Figure 1.
53
54
55
56
57
58
59
60

Component is an image of real world equipment, with : **Geometry**; **Behavior** (process logics, kinematics,...); **Interface**, configuration rules, material flows, signals,.

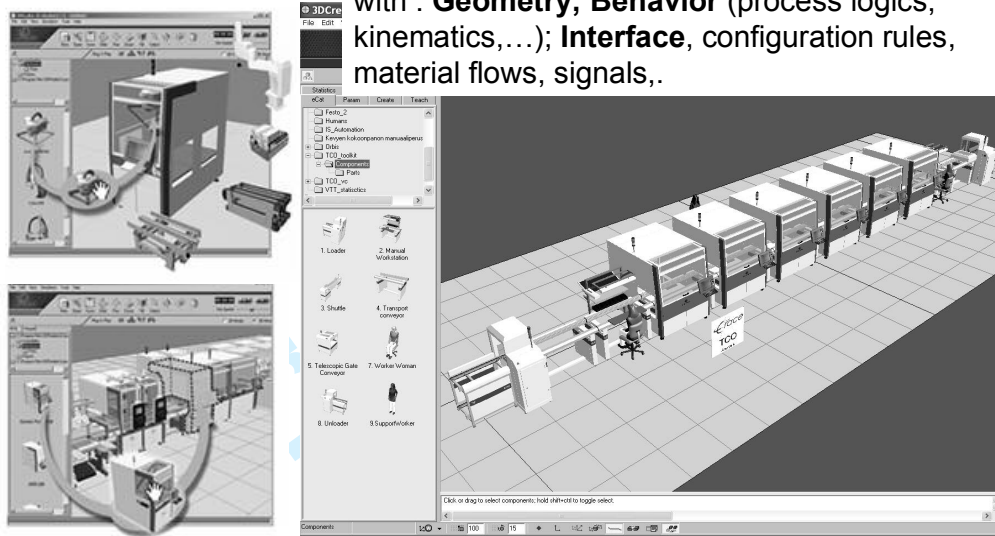


Figure 1: Component-based simulation is ideal for modular system design

Component-based simulation software is ideal for the design and configuration of modular reconfigurable systems. A suitable simulation tool, like [Visual Components, 2006], supports modularity at different levels: the workstation or basic process platform and process modules. The building blocks, "visual components", used in the simulation should be parametric in nature, have geometry, behaviour and interface just like real system modules. The use of simulation library components greatly speeds up model building. Library components have high reuse value and the 'build once, use multiple times' ideal is a reality. Model building with predefined modules is a process similar to 'drag and drop' or 'copy and paste'.

The authors believe that simulation, system modelling, COO and OEE are becoming increasingly important in high-tech decision-making processes as shown in the article. Systematic methods do improve the quality of decisions and communication. There is need for fast analysis, which could be carried out during a sales meeting and this is one of the development aims (See Figure 2). The difficulty is to get the right information for simulation analysis. Collaboration between system suppliers with equipment knowledge and end users with product and process knowledge does improve the accuracy of the simulation analysis.

The novelty of the development is in the integration of different analysis methods to improve the design of modular assembly systems. (See Figure 2. and 3)

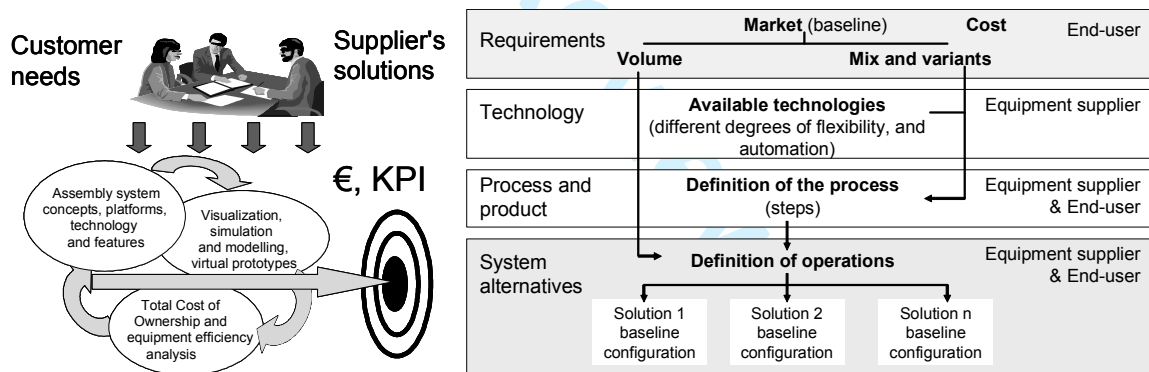


Figure 2: The development aims to improve design quality and communication.

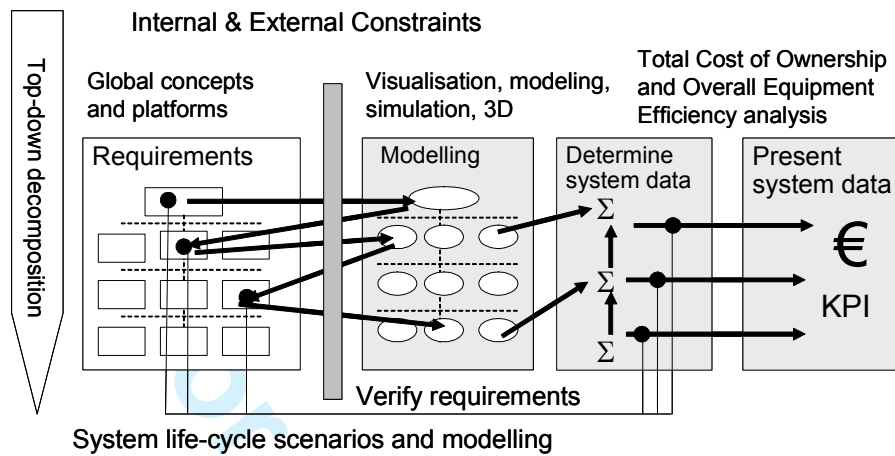


Figure 3: From requirements to assembly system cost efficiency

The development presented here is part of the Eureka Factory E!-2851 E-Race project, www.e-race.info. The national project consortium in Finland, research institutes, technology providers and end users worked together to create next-generation modular assembly systems and an enhance design methodology. This paper was originally presented in 2005 [Heilala *et al.* 2005a]. Now later advances [Heilala *et al.* 2005 b, Heilala *et al.* 2006] are summarised in this paper. The remainder of the paper is organised as follows. Sections 2 and 3 describe the theories behind the methodology and the integration of different analysis methods. In section 4, the methodology is presented through a case study. This is followed by an analysis and comparison of the developed methodology.

2. Theory for TCO methodology development

In this section, cost and efficiency analysis theories are briefly shown. The following chapter describes some commonly used life cycle cost analysis methods and the use of these methods.

2.1. Life Cycle and Cost of Ownership analysis

LCC for process industry. Life cycle costs (LCC) are summations of the estimated cost from inception to disposal for both equipment and projects as determined by an analytical study and an estimate of the total costs experienced during the life of equipment or projects (Barringer 1996). The objective of LCC analysis is to choose the most cost effective approach from a series of alternatives so that 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. LCC methodology is commonly used in process industry, often also applied to energy technologies and building projects.

TCO for Information Technology. Total Cost of Ownership (TCO) Modelling is a tool that systematically accounts 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 (Wikipedia 2006). 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.

1
2
3
4
5
6
7 *Other uses for TCO.* Similar TCO concepts are widely used in the automobile industry. In
8
9 this context, the TCO denotes the cost of owning a vehicle from the purchase, through
10
11 its maintenance, and finally its sale as a used car. Comparative TCO studies between
12
13 various car models help consumers choose a car to fit their needs and budget. TCO
14
15 methodology can be used for vendor selection and sourcing evaluation. [Wouters *et al*
16
17 2005, Degraeve *et al*, 2000, Degraeve and Roodhooft, 1999,]
18
19

20
21
22
23 *Standardised COO.* Cost of Ownership, COO, was initially created for the semiconductor
24
25 industry, wafer process step evaluation, and the methodology has been standardised.
26
27 The Semiconductor Equipment and Materials International (SEMI) standard (Semi E35,
28
29 2001) defines COO as the full cost of embedding, operating and decommissioning; in a
30
31 factory and laboratory environment, it is the system needed to accommodate a required
32
33 volume. Thus, in order to determine the COO of a piece of equipment, the full cost of
34
35 the equipment and its operation must be divided by the total number of good parts
36
37 produced over the commissioned lifetime of the equipment. The COO method has also
38
39 been used for optoelectronics (Ragona 2002), assembly, packaging and inspection in the
40
41 semiconductor industry (Dance *et al* 1996). COO is useful also in other technology
42
43 intensive industries.
44
45
46
47
48
49
50

51
52 As mentioned earlier, engineers and managers need to calculate all of the costs during
53
54 the lifetime of the equipment. The purchase price of the system is just one indicator of
55
56 the cost, as presented in the cost pyramid in Figure 4. There are many other costs and
57
58
59
60

some of the cost items are difficult to quantify or calculate. All of the parameters shown in Figure 4 are not covered in the SEMI E35 standard.

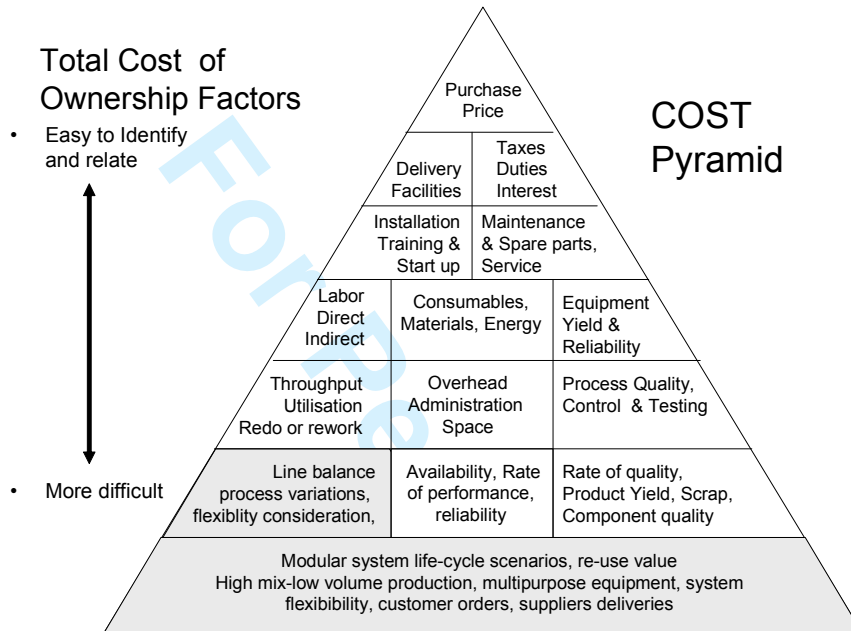


Figure 4: The Cost Pyramid modified from SEMI E35-0701.

2.2. The E-Race TCO analysis toolkit

The created tool concept is called the E-Race TCO analysis toolkit, even if analysis does not cover all of the possible costs. The focus is in assembly system design, system concept evaluation and system selection. The development is based on the selected methods shown in Figure 5. The development aims were to measure system performance in terms of overall equipment efficiency, OEE, other technical key performance factors and systems economic value in terms of life cycle and unit costs produced, COO. It could be the factor for winning a contract if the supplier can justify his system design on the basis of life cycle costs, and can include a complete life cycle

cost analysis in his proposal (i.e., cost breakdown structure, cost profile, etc.). Design engineers also need to estimate the efficiency of the system in terms of the number of good products produced. There are also benefits of using modern assembly system design tools - i.e. modelling, visualisation and 3D simulation - in the design process.

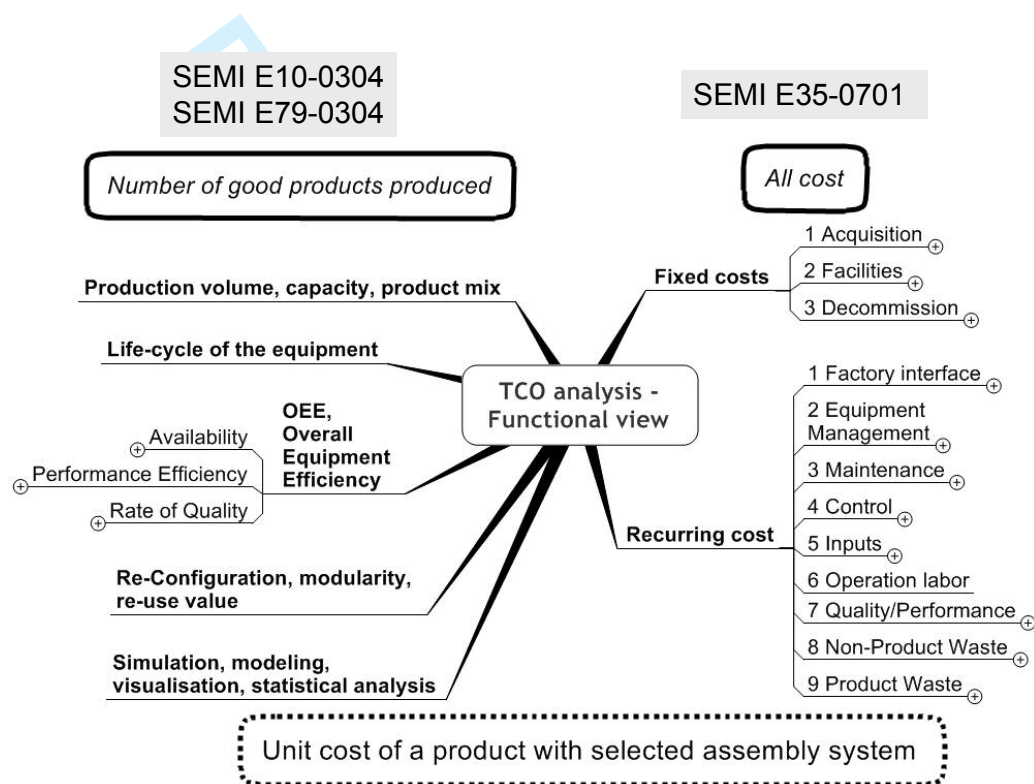


Figure 5. Methodology integration for E-Race TCO analysis toolkit

Overall Equipment Efficiency/Effectiveness, OEE, is used to measure existing equipment availability, efficiency, downtimes and quality rate. The authors are now proposing its use in the final assembly system design evaluation in the electromechanical industry. Simulation analysis and OEE metrics integration has been reported by [Huang, et al 2003] for manufacturing productivity improvement.

In the following chapters, the selected methods COO and OEE are shown in more detail.

2.3 Cost of ownership [SEMI E35-0701, Ragona 2002,]

The calculated COO value represents the cost of the process step for each good part produced. It indicates the cost added to that part of the process. The basics of COO are quite simple and can be summarised as follows:

$$\text{COO} = \text{Total costs during the system life} / \text{Total number of good parts}$$

The basic formula for COO can be written

$$\text{COO} = (\text{F€} + \text{L€} + \text{R€} + \text{Y€}) / (\text{L} \times \text{T} \times \text{Y} \times \text{U}) \quad (1)$$

Numerator Input Parameters

(See also Figure 5)

The total cost of owning the equipment consists of the sum of four major parameters

$$\text{Total cost} = \text{F€} + \text{L€} + \text{R€} + \text{Y€} \quad (2)$$

Where

F€ represents the initial fixed costs involved in purchasing the equipment: purchase price, cost of installation and initial training, system qualification

1
2
3
4 and any movement of the equipment within the factory, and any other
5 costs such as floor space usage, infrastructure needs and
6 decommissioning.
7
8
9

10
11
12
13
14 **L€** represents the fully burdened labour cost: production personnel,
15 operators needed to run the system. This is usually represented under **R€**
16 but in the case of an assembly system, personnel costs should also be
17 known.
18
19
20
21
22

23
24
25
26 **R€** represents the sum of all the re-occurring (variation) costs (excluding
27 labour, **L€**) associated with the equipment over its lifetime; it includes,
28 e.g., the factory interface, equipment management, consumables,
29 maintenance, utilities, floor rent and specialised support personnel. Note:
30 operation labour costs **L€** could also be included here.
31
32
33
34
35
36
37
38
39

40
41 **Y€** represents the yield cost associated with the equipment's mishandling
42 of the product. The cost of lost yield due to the equipment is obtained by
43 multiplying the probability of damage by the cost of the product at that
44 stage in the process. Yield costs include costs associated with scrap,
45 including breakage and equipment yield.
46
47
48
49
50
51
52

53
54 The yield cost is obtained by multiplying the number of defective
55 assemblies (**N**) directly attributable to the workstation by the values of the
56 parts at that stage of assembly (**P€**). Thus
57
58
59
60

$$Y\text{€} = N \times P\text{€} \quad (3)$$

Denominator Input Parameters

The total number of parts produced by the equipment is dependent on four major variables summarised in the equation below:

Total number of parts produced over the lifetime of the equipment = $L \times T \times Y \times U$

(4)

Where

L represents the entire lifetime of the equipment (normally 3-5 years for automated equipment)

T represents the throughput rate (parts per year or selected time)

Y represents the composite yield, which includes the cumulative effects of yield loss. The number of good units produced, **Y**, essentially represents a scaling factor, i.e., a value slightly less than one. Unfortunately, the yield parameter generally has the biggest impact on the COO value, but it is also the most difficult parameter to determine.

U represents equipment utilisation, which includes the impact of unscheduled maintenance, the mean time to repair scheduled maintenance,

1
2
3
4 assist time, production qualification time and process engineering time.

5
6
7 These major factors cause utilisation to be less than 100%.

8
9
10
11 One way of systematically estimating and classifying equipment efficiency and yield,
12 and also number of good-quality products, is to use OEE methodology as shown in the
13 next chapter.
14
15
16
17

18 19 20 21 *2.4 Overall Equipment Efficiency (OEE)*

22
23
24
25
26 The authors propose using OEE analysis to calculate or estimate the number of good-
27 quality products, and also to specify work time arrangements. Factory simulations could
28 also be used here, thus analysis methods partially overlap. The major difficulty is to
29 define the input data for the simulation and other analyses.
30
31
32
33

34
35
36
37
38 OEE is the most recent high-level equipment performance metric. It was developed as
39 an equipment effectiveness metric in Japan to measure the effectiveness of a
40 manufacturing technique called Total Productive Maintenance (TPM). It was originally
41 called Overall Equipment Effectiveness. The Semiconductor Equipment and Materials
42 International (SEMI) Metrics Committee changed it to Overall Equipment Efficiency,
43 and the methodology is standardised (SEMI E10-0304, SEMI E79-0304).
44
45
46
47
48
49
50
51

52
53
54 The OEE is commonly used for monitoring the running performance of shop floor
55 equipment. OEE is a key performance indicator of how machines, production lines or
56 processes are performing in terms of equipment availability: reliability (MTBF),
57
58
59
60

1
2
3
4 maintainability (MTTR), utilisation, throughput performance or speed and quality
5 produced (yield). It identifies losses due to equipment failure, set-ups and adjustments,
6
7 idling and minor stops, reduced speed, process defects and start up. Thus, OEE is an all-
8
9 inclusive metric of equipment productivity. All of the above factors are grouped under
10
11 the following three sub-metrics of equipment efficiency:
12
13

- 14 1. Availability
 - 15 2. Performance efficiency
 - 16 3. Rate of quality
- 17
18
19
20
21
22
23
24
25

26 The three sub-metrics and OEE are mathematically related as follows:

$$27 \text{OEE, \%} = \text{availability} \times \text{performance efficiency} \times \text{rate of quality} \times 100$$

28
29
30
31
32

33 General information on OEE can also be obtained from www.oee.com or other Internet
34 sources. There are different opinions on how to calculate OEE and how to translate the
35 acronym - is the last E for Efficiency or Effectiveness? The important factor is to
36 systematically use the same approach all the time, so that it is possible to compare
37 results. The Overall Equipment Efficiency analysis method developed and used by
38 authors is based on SEMI standards. There is a systematic way to classify and study
39 equipment efficiency and time losses (See Figure 6 and Table 1).
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

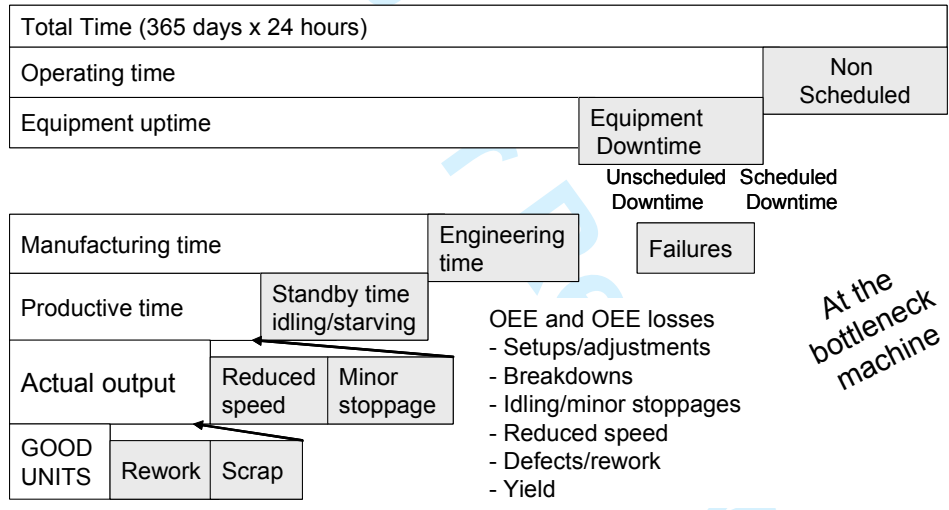
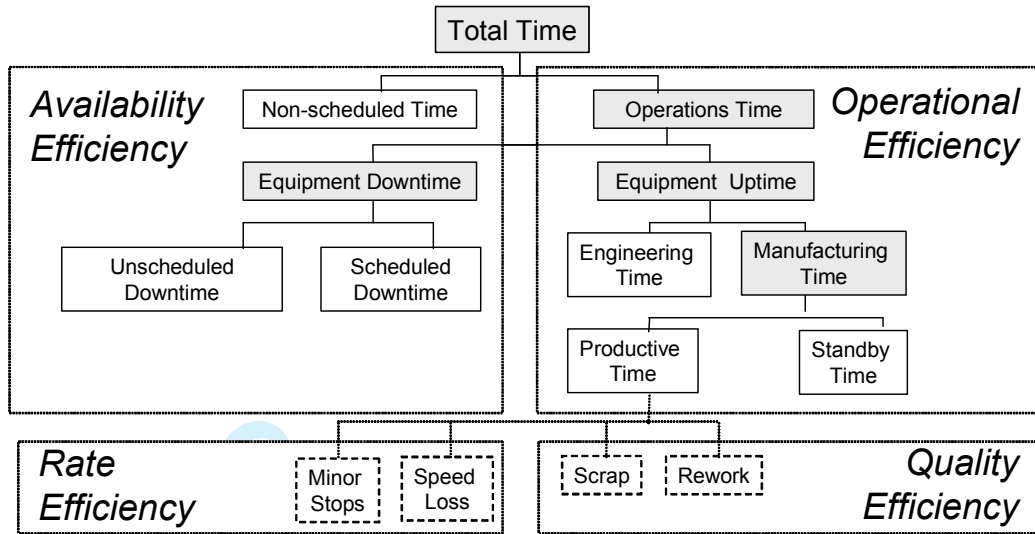


Figure 6: Classification of production time upper level.

Table 1. OEE Six big losses.

OEE efficiency calculations	Major OEE losses	Losses sub-category	SEMI E10 efficiency calculations
Availability	Set-ups/adjustments Breakdowns	Non-scheduled Preventative maintenance Qualifications Set-up Equipment failure Process failure Facility failure	Non-scheduled time Scheduled downtime Unscheduled downtime
Performance efficiency	Idling/minor stoppages Reduced speed	Engineering No product No operator Limited capacity Slow speed Stoppage/assist	Engineering time Standby/idle time Other time losses Tool speed losses Average batch size Productive
Rate of quality	Defects/rework Yield	Rework Scrap	Quality losses

The production engineer should know the production loss factors. This is a way to analyse effective productive time and thus also the number of good units produced. The theoretical optimum cycle time without this kind of analysis overestimates production capacity. This is also a tool for the continuous improvement of a running system.

3 Methodology developments

Based on the standardised methodology presented in section 2, the authors have developed E-race TCO, Total Cost of Ownership, analysis Excel workbook. Suitable definitions are used and adapted for electromechanical final assembly system design evaluation. The keywords in analysis are decomposition, cost data and operating time classification. Both the efficiency analysis and cost analysis factors are divided into

smaller units. Secondly, there is a life cycle aspect as well: cost is divided according to the operational lifetime of the system.

Fixed cost sub-classes are presented in Table 2 and recurring cost sub-classes in Table

3. The cost sub-classes are similar to SEMI E35-0701 standard definitions, but some of the cost classes defined in the standard have not been used.

Table 2. Fixed cost sub-classes, modified from SEMI E35-0701

Functional - Fixed cost	Units	Year 1	Year 2	...	Year n
F1.0 Acquisition	€				
F1.1 Acquisition: Price	€				
F1.2 Acquisition: Purchasing	€				
F1.3 Acquisition: Evaluation	€				
F1.4 Acquisition: Installation	€				
F1.5 Acquisition: Training	days				
F1.5.1 Acquisition: Training	€				
F2.0 Facilities	€				
F2.1 Facilities: Space	m ²				
F2.1.1 Facilities: Space - cost	€				
F2.2 Facilities: Infrastructure	€				
F2.2.1 Facilities: Infrastructure: Utilities	€				
F2.2.2 Facilities: Infrastructure: Services	€				
F3.0 Decommissioning	€				
F3.1 Decommissioning: Removal	€				
F3.2 Decommissioning: Disposal	€				
F3.3 Decommissioning: Cleanup	€				

Table 3. Recurring cost sub-classes, modified from SEMI E35-0701

Functional - Recurring cost	units	Year 1	Year 2		Year n
R1.0 Factory Interface	€				
R1.1 Factory Interface: Labour	Persons				
R1.1 Factory Interface: Labour – cost	€				
R1.2 Factory Interface: Safety	€				
R1.4 Factory Interface: Infrastructure	€				
R2.0 Equipment Management	€				
R2.1 Equipment Management: Supervision	Persons				
R2.1.1 Equipment Management: Supervision - cost	€				
R2.2 Equipment Management: Support	Persons				
R2.2.1 Equipment Management: Support - cost	€				
R2.3 Equipment Management: Administration	Persons				
R2.3.1 Equipment Management: Administration - cost	€				
R3.0 Maintenance	€				
R3.1 Maintenance: Service Contracts	€				
R3.2 Maintenance: Labour-Other	Persons				
R3.2.1 Maintenance: Labour-Other - cost	€				
R3.3 Maintenance: Spare Parts	€				
R3.4 Maintenance: Repair Parts	€				
R4.0 Control	€				
R4.1 Control: Software	€				
R4.2 Control: Training	Days*Person				
R4.2.1 Control: Training – cost	€				
R4.3 Control: Support	Days*Person				
R4.3.1 Control: Support - cost	€				
R4.4 Control: Backup	€				
R5.0 Inputs	€				
R5.1 Inputs: Consumables	€				
R5.2 Inputs: Material	€/product				
R5.2 Inputs: Material – cost	€				
R5.3 Inputs: Utilities	€				
R6.0 Operation Labour	€				
R6.0.1 Operation Labour	Persons				
R9.0 Product Waste	€				
R9.3 Scrap: Yield loss					
R9.3.1 Scrap: Yield loss - cost	€				
R9.4 Rework	nbr				
R9.4.1 Rework – cost	€				

Similarly, efficiency and production volume is analysed using OEE methodology time elements have been classified, see Figure 6.

3.1 E-Race TCO analysis tool prototype

The development started as an Excel spreadsheet application having separate workbooks for OEE and COO analysis. Simulation was only used as a system configuration and layout visualisation, all data was manually entered into the Excel sheets. Later, both COO and OEE were in the same workbook and the TCO Excel workbook integration to commercial component-based simulation was created.

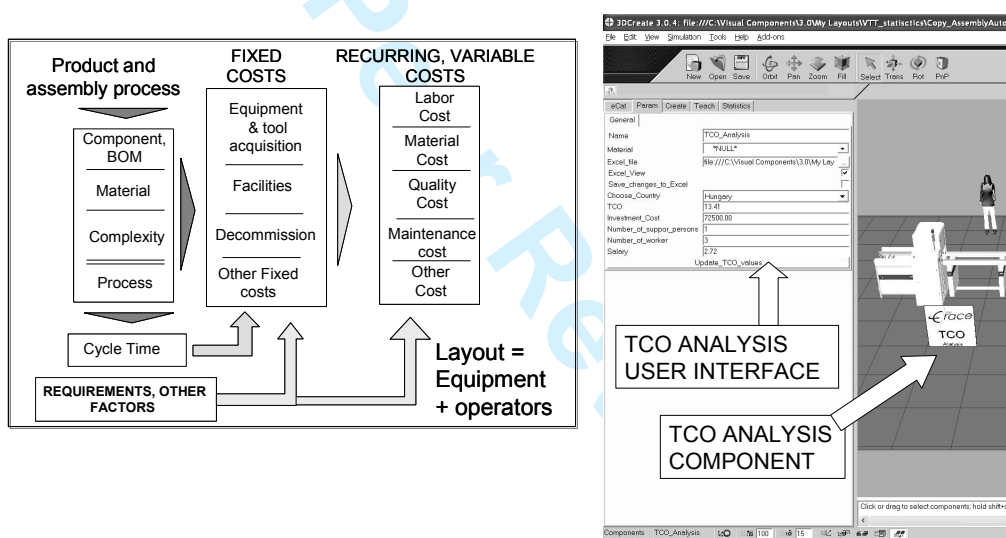


Figure 7. Using the TCO analysis component.

The first TCO analysis component was programmed using the Python language and has an interactive user interface (Figure 7). The layout data from the simulation model was used to provide information about equipment and operator components in the virtual model. Other cost classes must be entered into the Excel sheets manually or the default values must be accepted. The simulation model reads and writes data to the selected cell in the Excel workbook and thus the integration is limited. In the latest existing

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

prototype, there is semi-automated interaction between different parts of analysis, i.e., Excel calculations and simulation runs. The advanced version uses a COM interface and Excel-internal links. Each time an engineer selects a component from eCatalogue, a machine or operator, and places it in a simulation model layout, the cost functions start adding equipment and labour cost functions interactively. The actual simulation run results are not automatically used, but can be used as input or for OEE analysis or to verify OEE analysis depending on how the simulation model is built and what kinds of input data are available. An overview of the development is given in Figure 8.

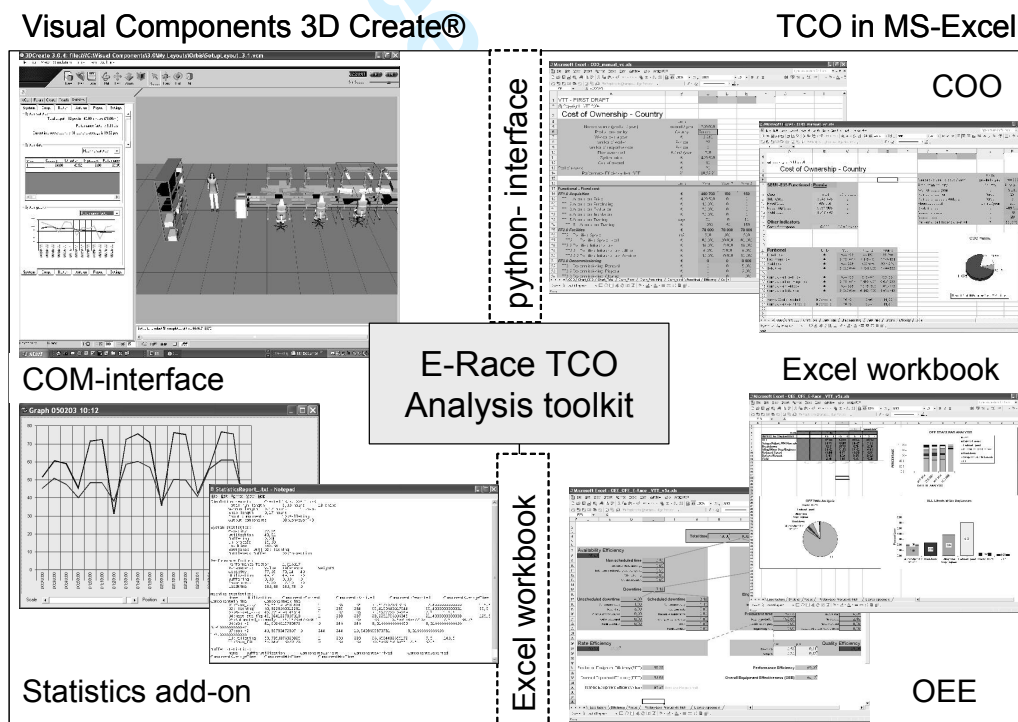


Figure 8. Overview of the TCO analysis toolkit.

In The E-Race TCO Analysis toolkit, the same Excel workbook can be used for analysis with or without simulation software if the engineer inputs all of the necessary data manually. Integration of Total Cost of Ownership (TCO) analysis into the simulation

provides an effective method of evaluating system alternatives from the cost standpoint during model building. This is clearly a tool for the system sales engineer. Adding easy-to-use economic analysis features to the simulation improves the quality of decisions during a sales meeting.

3.2 Analysis flow

The following shows the interactive nature of the analysis. Using OEE analysis, the engineer can evaluate production volumes from given input values. The theoretical throughputs - i.e., cycle times - need to be known as well as the process descriptions.

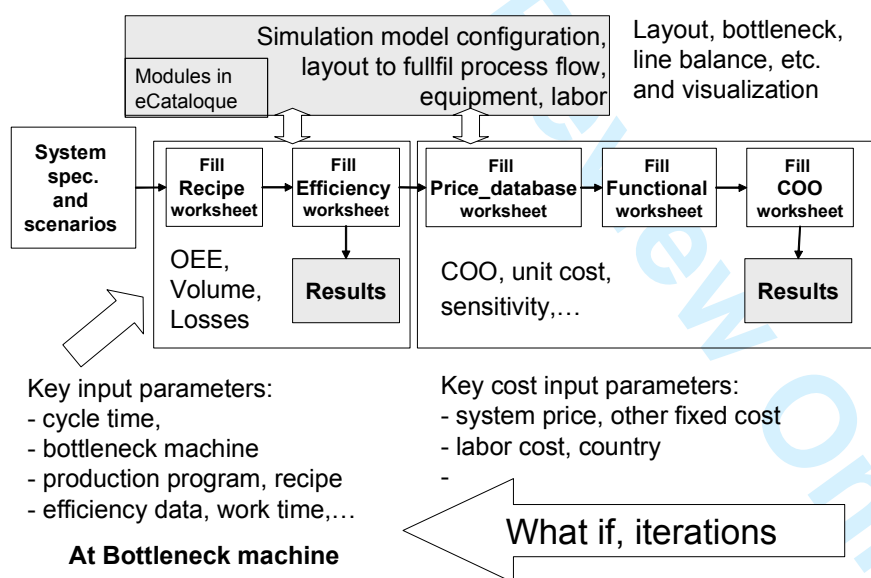


Figure 9. Analysis workflow, iterative steps not shown.

Regarding the volume, one key factor is work time arrangements; adding shifts increases capacity, and increases variable costs. The OEE analysis also shows the major loss factors with given input parameters.

1
2
3
4
5
6
7 The next step is to start thinking about the equipment needed to fulfil the process flow
8
9 and other requirements. In the case of a modular assembly system, the price of the
10
11 system is defined while selecting suitable "standardised" equipment and designing the
12
13 system layout to fulfil the required process flow. The labour cost is defined with the
14
15 equipment selection and degree of automation. Equipment price, need for operators and
16
17 consumables, and components for the product need to be known for calculating unit
18
19 costs. All of the other fixed and recurring cost parameters used are shown in Tables 2
20
21 and 3. The analysis is iterative and the engineer might need to go back to a previous
22
23 step until cost, performance and other criteria are fulfilled
24
25
26
27
28
29

30 The end user and the system supplier could feed the input parameters collaboratively
31
32 during the sales meeting. The end user has knowledge of the product and processes
33
34 needed in the assembly and the system supplier has knowledge of the equipment. An
35
36 assembly system can be evaluated and thus data created for comparison and trade-off
37
38 analysis.
39
40
41
42
43

44 The following section illustrates the use of TCO analysis.
45
46
47
48

49 **4. Case analysis**

50
51
52
53

54 The fictitious case study shows the use of the E-Race TCO analysis in assembly line
55
56 design. The initial data was as follows: needed production volume about 200,000 units
57
58 per year and the estimated lifetime of the product, and the assembly line, was 3 years.
59
60

1
2
3
4 The workflow was serial, with 10 work phases and 13 components. The cost of the
5 components for the product was about 10 €, and the rework cost at the production line
6 was about 20 €.
7
8
9

10
11
12
13
14 The takt times of the system were based on time studies and estimations of bottleneck
15 equipment are not shown here. The takt time for the automated line was about 24
16 seconds and for the semi-automated line about 72 seconds. There are two different basic
17 semi-automated solutions: three identical assembly lines in one shift, or one semi-
18 automated assembly line in three shifts. The purchase cost of one assembly line is
19 136,500 € and each assembly line needs 9 operators and 2 support persons. There are
20 two options for production countries, in a Western Europe country or an Eastern low-
21 labour-cost country. The automated system purchase price is 643,000 € with 2 operators
22 and 1 support person. The automated line worked in one shift.
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37

38 There were four basic solutions, scenarios for the assembly system:

- 39
40 - Eastern Semi-automated system, three identical lines in one shift (ES L1S1)
41
42 - Eastern Semi-automated system, one line in three shifts (ES L1S3).
43
44 - Western Semi-automated system, one line in three shifts (WS LIS3)
45
46 - Western Automated line, one line in one shift (WA L1S1). .
47
48
49
50

51
52 Many of potential parameters available in the TCO analysis were constant, since the
53 idea was to make a quick analysis of the alternatives - manual or automated assembly
54 tasks - and also to study the effects of manufacturing in a low-labour-cost country. The
55 comparison was between Russia and Sweden.
56
57
58
59
60

4.1 OEE and volume analysis

The first step was to study OEE Loss factors and, naturally, calculate the volume. The results and parameters are shown in Table 4.

Table 4. Table OEE, Volume and Loss Factors

Parameters	1 shift, S1	3 shifts, S3
workdays/week	5	5
shifts/day	1	3
shift length [hr]	7.5	7.5
Calculated volume, products/year	213 785	235 164
Overall Equipment Effectiveness (OEE), %	15.59	51.45
Performance Efficiency in OEE, %	89.04	91.26
Quality Efficiency in OEE, %	89.44	90.31
Availability Efficiency in OEE, %	19.58	62.43
Big losses		
Set-ups/Adjust./PM Non-scheduled.	79.53	34.89
Breakdowns	0.89	2.68
Idling/Minor Stop/Engineer	1.39	2.98
Reduced Speed	0.76	2.48
Defects/Rework	1.52	4.56
Yield	0.32	0.96

There were only these two OEE settings in the scenarios. The effects of these parameters on the unit's cost can also be studied. The OEE also shows the potential for capacity flexibility. The major OEE losses are shown there to focus on increasing productivity. Deeper analysis of the efficiency factors depends on the system concept, operator's skill and so on and could be studied. Figure 10 shows the OEE sheet of the TCO calculation, which was used to calculate the parameters for Table 4.

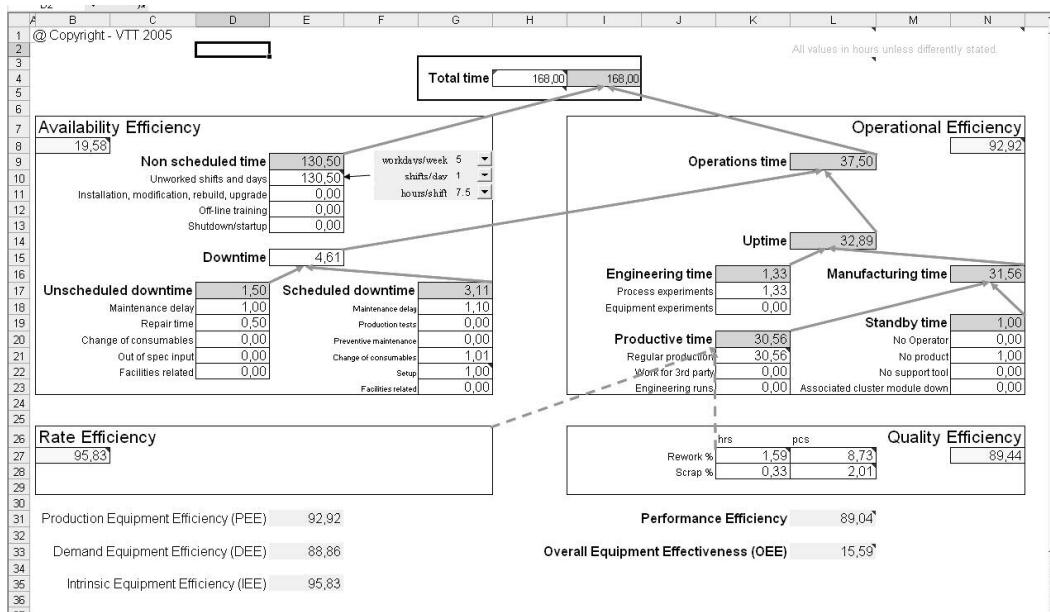


Figure 10. OEE data for 3-shift arrangement.

4.2 Semi-Automated Assembly Lines

The main assembly tasks are manual, but material flow and testing is automated (Figure 11). As a starting parameter, a single-shift over 5 days a week was estimated thus having three identical lines to reach the required volume. Optionally, a scenario with one line having three shifts was also analysed (see Table 4 for OEE values).

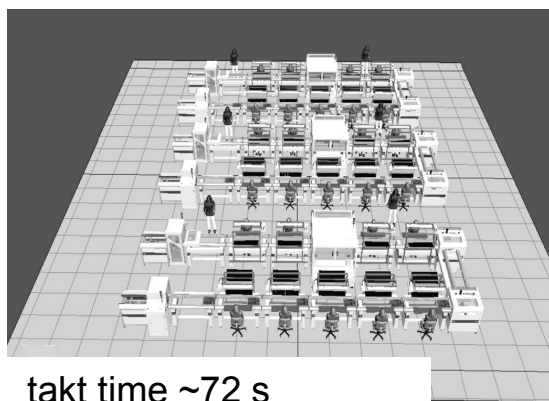


Figure 11: Semi-automated assembly lines.

As an example, only the upper level results are presented here. The parameters are divided into sub-classes and life cycle in years, as shown in the previous section. Using the model, managers and engineers can see whether the system price forms a large fraction of the fixed price (see the following Tables).

Table 5. Semi-automated lines input values for COO

Major input	Unit	Scenario ES L3S1	Scenario ES L1S32
Calculated volume (product / year)	product / year	213 785	235 164
Production country	Country	Russia	Russia
Worker cost per year	€	3 910	3 910
Number of workers	Person	27	9 x 3
Number of support workers	Person	6	2 x 3
System price	€	409 500	136 500

OEE data can be found in Table 4. The unit cost, COO for scenario ES L3S1, is 12.47 €/product. To minimise investment, just purchase one assembly line and operate it in three shifts. Then the unit cost, COO for scenario ES L1S3, is 11.50 €/product. The following Tables show the scenario results, yearly and cumulative costs.

Table 6. Summary results for scenario ES L3S1, three lines in one shift.

Funtional	Units	Year 1	Year 2	Year 3
Fixed Cost	€	544 119	71,209	71 209
Recurring Cost	€	2 414 690	2 414 284	2 414 284
Yield cost	€	22 947	22 947	22 947
Total Cost	€	2 981 756	2 508 440	2 508 440
Cumulative Fixed Cost	€	544 119	615 328	686 537
Cumulative Recurring Cost	€	2 414 690	4 828 974	7 243 258
Cumulative Yield cost	€	22 947	45 894	68 841
Cumulative Total Cost	€	2 981 756	5 490 196	7 998 636
Yearly Cost / Product	€ / product	13.947	11.733	11.733
Cumulative Cost / Product	€ / product	13.947	12.840	12.471

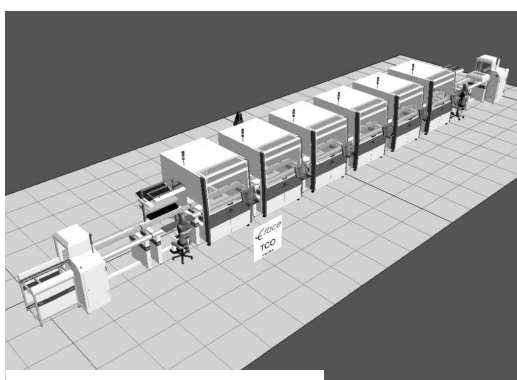
Table 7. Summary results for scenario ES L1S3, one line in three shifts.

Functional	Units	Year 1	Year 2	Year 3
Fixed Cost	€	209 694	50 734	50 734
Recurring Cost	€	2 576 820	2 576 414	2 576 414
Yield cost	€	23 136	23 136	23 136
Total Cost	€	2 809 649	2 650 283	2 650 283
Cumulative Fixed Cost	€	209 694	260 428	311 162
Cumulative Recurring Cost	€	2 576 820	5 153 233	7 729 647
Cumulative Yield cost	€	23 136	46 271	69 407
Cumulative Total Cost	€	2 809 649	5 459 933	8 110 216
Yearly Cost / Product	€ / product	11.948	11.270	11.270
Cumulative Cost / Product	€ / product	11.948	11.609	11.496

Similarly, scenario WS L1S3, one line in three shifts in a Western country was calculated, the unit cost, COO is 18.77 €/product. For a full comparison, see Table 8

4.3 Automated Assembly Line

The automated assembly line (Figure 12) was similarly analysed; the data tables are not shown here. As a starting parameter, operation in a single shift over 5 days a week is used and the production country is Sweden.



takt time ~24 s

Figure 12: Automated assembly line.

COO is 14.31 €/product. OEE values are in Table 4. A full comparison can be found in Table 8-

4.4 Comparison of case scenarios results

The idea is to first compare the assembly system alternatives with the same system parameters, and later to perform a more accurate analysis. In the concept evaluation, the engineers might not have very accurate data available. Table 8 shows the first-round analysis results; the same efficiency and quality levels were used. In Table 8, Evaluation of concept scenarios, the country is identified with W or E; S means manual assembly tasks, A automated assembly tasks, L indicates the number of lines, S1 or S3 indicates the number of shifts. The material flow was automated in all cases, as shown in Figures 11 and 12.

Table 8. Evaluation of concept scenarios

Results	Russia ES L1S3	Sweden WA L1S3	Sweden WS L1S3	Russia ES L3S1
COO, € / product	11.50	18.77	14.31	12.47
Total Cost [€]	8 110 216	13 239 864	9 177 761	7 998 636
Fixed Cost [€]	311 162	350 783	1 008 043	686 537
Recurring Cost [€]	7 729 647	12 819 674	8 100 877	7 243 258
Yield cost [€]	69 407	69 407	68 841	68 841
Overall Equipment Effectiveness (OEE), %	51.45	51.45	15.59	15.59
Performance Efficiency from OEE, %	91.26	91.26	89.04	89.04
Quality Efficiency from OEE, %	90.31	90.31	89.44	89.44
Availability Efficiency from OEE, %	62.43	62.43	19.58	19.58
Calculated volume (product / year)	235 164	235 164	213 785	213 785
Parameters				

Production country	Russia	Sweden	Sweden	Russia
Worker cost per year [€]	3 910	48 505	48 505	3 910
Number of workers	27	27	2	27
Number of support workers	6	6	1	6
System price [€]	136 500	136 500	643 000	409 500
Cost of product [€]	10.19	10.19	10.20	10.20
Cost of rework [€]	20.37	20.37	20.41	20.41
workdays/week	5	5	5	5
shifts/day	3	3	1	1
shift length [hr]	7.5	7.5	7.5	7.5

To summarise, in case the production remains in a western country like Sweden, then automate; in a low-labour-cost country, try running one line in three shifts. In the case of having only one assembly line, there are limitations on capacity flexibility. If managers do estimate that future capacity can be more than one line can produce while working 24 hours a day, 7 days a week, they should also study scenarios with more than one assembly line.

In the second stage of the analysis, the engineers should go deeper into the parameters and perform a what-if analysis, if reasonably accurate data is available. At least the effects of yield, quality and cost should be analysed. Risk analysis can be carried out by maximising or minimising values, thus finding the minimum and maximum for COO. One of the biggest challenges is get the right data. Engineers are able to build very efficient assembly lines, but what if there are no orders?

4.5 Discussion

Prototypes of the tools already exist, as shown here; deeper integration is in progress, as well as case studies with real industrial data. The methodology is scaleable, from a

1
2
3
4 single machine to factory level. The results are naturally more accurate at the
5
6 workstation level. In the case of analysing an assembly line, the current TCO model
7
8 uses throughput data from the bottleneck machine and also yield data from the line as
9
10 just one figure. For a more precise analysis, engineers need to have all data at single
11
12 machine level and combine data at line level; currently this can be done by creating a
13
14 model for each machine and the user manually collating the data at assembly line level.
15
16 Automating this enhancement will be studied in a new research project.
17
18
19
20
21
22

23 Even if the development is called Total Cost of Ownership, it is very difficult get data
24
25 for all of the cost factors. The focus is in system design and the cost of operating it.
26
27 Some overhead-type costs are not calculated directly, for example, upper level
28
29 management costs.
30
31
32
33
34

35 The COO standard used in the development has been updated - the latest release is 2005
36
37 - but the authors used the 2001 release. There is a similar commercial tool available,
38
39 dedicated to the semiconductor industry, originally developed together with The
40
41 Semiconductor Equipment and Materials International (SEMI). More information is
42
43 available at www.wwk.com. Some cost analysis can be carried out as part of the DFA
44
45 (Design for Assembly) analysis; the DFA cost analysis does not calculate yield cost.
46
47
48
49
50
51

52 The novelty of the development presented here is in the integration of different
53
54 methods. The development aim was to build an analysis system to be used by the
55
56 system sales engineer for testing different alternatives during the sales meeting with
57
58 customers. A modular assembly system can easily be configured and system layout
59
60

1
2
3
4 visualised with component-based simulation. The development work presented brings
5
6 economic analysis integrated with simulation model building. It could be the factor for
7
8 winning contracts if the supplier can justify his design on the basis of life cycle costs,
9
10 and can include a complete life cycle cost analysis in his proposal (i.e., cost breakdown
11
12 structure, cost profile, etc.).
13
14

15 16 17 18 **5 Conclusions** 19

20
21
22
23 Selecting the most appropriate assembly system can offer enormous benefits in terms of
24
25 product quality, cost reduction and manufacturing productivity. However, selecting the
26
27 right system for a product depends on a large number of factors and is not a simple
28
29 problem. This paper proposes a systematic approach to support decision-making in this
30
31 area and presents a methodology for selecting assembly systems for a product based on
32
33 technological, efficiency and economic considerations. This paper also presents a case
34
35 study in the design of a modular reconfigurable final assembly system using simulation,
36
37 and system life cycle and cost analysis methodology. The theory behind the analysis is
38
39 also briefly explained.
40
41
42
43
44
45
46

47
48 The basic equation presented here for calculating the COO was originally developed for
49
50 wafer fabrication tools and has become a common term among equipment suppliers and
51
52 equipment users in the semiconductor industry; COO methodology is not well known in
53
54 the arena of electromechanical assembly.
55
56
57
58
59
60

1
2
3
4 Cost of ownership provides an objective analysis method for evaluating decisions. COO
5
6 can be an implementation of Activity-Based Costing (ABC) that helps in understanding
7
8 all costs associated with a decision. It improves decisions by relating the costs to the
9
10 products, processes and services that drive the cost. COO provides an estimate of the
11
12 life cycle cost. Without such a linkage, it is difficult for organisations to understand the
13
14 full impact of their decisions on their operating cost structure. With this linkage, COO
15
16 provides a consistent data-driven method for arriving at important strategic and
17
18 operational decisions. The analysis highlights details that might be overlooked, thus
19
20 reducing decision risk.
21
22
23
24
25
26
27

28 Finally, COO allows communication between suppliers and users. They are able to
29
30 speak the same language, comparing similar data and costs using the same analysis
31
32 methods. Both suppliers and manufacturers can work from verifiable data to support a
33
34 purchase or implementation plan. The lifetime cost of ownership per manufactured unit
35
36 is generally sensitive to production throughput rates, overall reliability and yield. In
37
38 many cases, it is relatively insensitive to the initial purchase price; this can be
39
40 pinpointed with proper use of analysis. Using the correct parameters, an engineer can
41
42 justify investments in flexibility and automated equipment, or at least determine
43
44 threshold values.
45
46
47
48
49
50

51 OEE is usually a measurement of single machine performance. In the example
52
53 presented, the calculations are used for a bottleneck machine and, in practice, the
54
55 Overall Throughput Efficiency of the assembly line is calculated. With a serial line and
56
57 one product, as used in the example, this can be quite simple. The analysis is more
58
59
60

1
2
3
4 complex with mixed production and a layout with parallel operations. Simulation
5
6 studies can pinpoint bottleneck equipment. One of the limitations of using OEE analysis
7
8 is that the analysis is process- or equipment-centric and the material flow or work in
9
10 progress (WIP) is not analysed - another reason for using factory simulations.
11
12

13
14
15
16 Users should remember that, as with all simulation analyses, this kind of simulation is
17
18 sensitive to the input data, and that input of false information does not produce the right
19
20 results. The challenge is in getting the correct data. Knowing this, the authors are not
21
22 aiming at absolute results in the design phase, but, rather, at obtaining data for the
23
24 comparison of design alternatives. Later, real factory data and accounting data can be
25
26 used to verify the models and thus improve the results during the next evaluation round
27
28 and in new system designs.
29
30
31
32

33
34
35 The authors believe that COO, OEE, modelling and simulation are becoming
36
37 increasingly important in high-tech decision-making processes. The challenge is to
38
39 bring system reconfiguration to the analysis automatically; the idea only exists at a
40
41 conceptual level. Now, reconfiguration and system modularity cost-efficiency analysis
42
43 requires a lot of manual work.
44
45
46
47
48

49 6 Further Work

50
51
52

53
54 The developed TCO prototype tools are currently proof of the concept. The
55
56 development aspects discussed here are the subject of further research currently being
57
58 undertaken at VTT in a new research project. The cost modelling will be validated with
59
60

1
2
3
4 real case studies. The focus will be on integration with simulations, factory modelling,
5
6 material flow and system life cycle scenarios. Other productivity metrics and flexibility
7
8 issues will also be studied. The aims are to improve integration of the analysis into the
9
10 component-based simulation software and to obtain analysis data from simulation input
11
12 data files, and from the results of simulation runs, with minimum effort from the users.
13
14
15
16
17

18 **Acknowledgements**

19
20 The authors wish to acknowledge the financial support received from the Finnish
21
22 Funding Agency for Technology and Innovation (TEKES), VTT and Finnish industry.
23
24 The development is part of the Eureka Factory E!-2851 E-Race project. The national
25
26 project consortium in Finland, research institutes, technology providers and end users
27
28 worked together to enhance assembly systems design methodology.
29
30
31
32
33
34

35 **References**

- 36
37 Barringer, H. Paul and David P. Weber, 1996, "Life Cycle Cost Tutorial", Fifth
38
39 International Conference on Process Plant Reliability October 2-4, 1996,, Gulf
40
41 Publishing Company, Houston, TX, available from <http://www.barringer1.com>
42
43
44 Chow, We-Min. Assembly Line Design, Methodology and Applications. Marcel
45
46 Dekker, Inc., New York and Basel, 1990.
47
48
49 Dance, Daren L., DiFloria, Thomas, and Jimenez, David W. Modeling the Cost of
50
51 Ownership of Assembly and Inspection. IEEE Transactions On Components,
52
53 Packaging, And Manufacturing Technology-Part C, Volume. 19, NO. 1, January
54
55 1996. Pages 57-60.
56
57
58
59
60

- 1
2
3
4 Degraeve, Z., Labro, E. and Roodhooft, F. An evaluation of vendor selection models
5
6 from a total cost of ownership perspective. *European Journal of Operational*
7
8
9
10
11
12 Degraeve, Z. and Roodhooft, F., Improving the efficiency of the purchasing process
13
14 using total cost of ownership information: The case of heating electrodes at
15
16 Cockerill Sambre S.A. *European Journal of Operational Research*, Volume 112,
17
18 Issue 1, 1 January 1999, Pages 42-53
19
20
21 E-Race. <http://www.e-race.info/> International project web site. accessed 15 December
22
23 2005
24
25
26 Heilala, J.; Helin, K.; Montonen, J.. 2005a. Total cost of ownership analysis for modular
27
28 final assembly systems. 18th International Conference on Production Research,
29
30 ICPR 18. Salerno, 31 July - 4 August 2005. University of Salerno
31
32
33 Heilala, J.; Helin, K.; Montonen, J.; Voho, P. and Anttila, M.. 2005b. Integrating cost of
34
35 ownership analysis into component-based simulation. CARV2005 Today's
36
37 Reactions Tomorrow's Challenges. 1st Int. Conf. on Changeable, Agile,
38
39 Reconfigurable and Virtual Production. München, 22 - 23 Sept. 2005. Technische
40
41 Universität München, ss. 385 - 392
42
43
44 Heilala, J., Helin, K., Montonen, J. and Väättäin, O. Life Cycle And Cost Analysis For
45
46 Modular Re-Configurable Final Assembly Systems. Third International Precision
47
48 Assembly Seminar IPAS'2006 Bad Hofgastein, Austria, 19-22 February 2006.
49
50
51
52 Huang, Samuel H., Dismukes, John P., Shi, J., Su, Qi, Razzak Mousalam A., Bodhale
53
54 Rohit and Robinson D. Eugene . Manufacturing productivity improvement using
55
56 effectiveness metrics and simulation analysis. *International Journal of Production*
57
58
59 Research, 2003, Volume. 41, no. 3, 513–527
60

1
2
3
4 Ragona Sid, Cost Of Ownership (COO) For Optoelectronic Manufacturing Equipment.

5
6 2002. Microsystems Conference. Rochester, N.Y, 200. available at

7
8
9 <http://documents.exfo.com/appnotes/anoteBurleigh002-ang.pdf>

10
11 SEMI E35-0701, 2001, Cost of Ownership for Semiconductor Manufacturing

12
13 Equipment Metrics, SEMI International Standard, <http://www.semi.org>.

14
15 SEMI E10-0304, 2004, Specification for Definition and Measurement of Equipment

16
17 Reliability, Availability, and Maintainability (RAM), SEMI International

18
19 Standard, <http://www.semi.org>.

20
21 SEMI E79-0304, 2004, Specification for Definition and Measurement of Equipment

22
23 Productivity, SEMI International Standard, <http://www.semi.org>

24
25
26
27
28 www.oee.com, accessed 15 December 2005

29
30 Visual Components, <http://www.visualcomponents.com/portal/company/> accessed 15

31
32
33 December 2005

34
35 Wright Williams & Kelly, <http://www.wwk.com/>, accessed 15 December 2005

36
37 Wouters, Marc, Anderson James C. and Wynstra, Finn. The adoption of total cost of

38
39 ownership for sourcing decisions-a structural equations analysis. Accounting,

40
41 Organizations and Society, Volume 30, Issue 2, February 2005, Pages 167-191

42
43
44 Wikipedia (2006). Total cost of ownership.

45
46
47 http://en.wikipedia.org/wiki/Total_cost_of_ownership. accessed 12.4.2006

List of Figures:

- Figure 1: Component-based simulation is ideal for modular system design
Figure 2: The development aims to improve design quality and communication.
Figure 3: Form requirements to assembly system cost efficiency
Figure 4: The Cost Pyramid modified from SEMI E35-0701.
Figure 5. Methodology integration for E-Race TCO analysis toolkit
Figure 6: Classification of production time upper level.
Figure 7. Using the TCO analysis component.
Figure 8. Overview of the TCO analysis toolkit.
Figure 9. Analysis workflow, iterative steps not shown.
Figure 10. OEE data for 3-shift arrangement.
Figure 11: Semi-automated assembly lines.
Figure 12: Automated assembly line.

List of Tables

- Table 1. OEE Six big losses.
Table 2. Fixed cost sub-classes, modified from SEMI E35-0701
Table 3. Recurring cost sub-classes, modified from SEMI E35-0701
Table 4. Table OEE, Volume and Loss Factors
Table 5. Semi-automated lines input values for COO
Table 6. Summary results for scenario ES L3S1, three lines in one shift.
Table 7. Summary results for scenario ES L1S3, one line in three shifts.
Table 8. Evaluation of concept scenarios

Figures

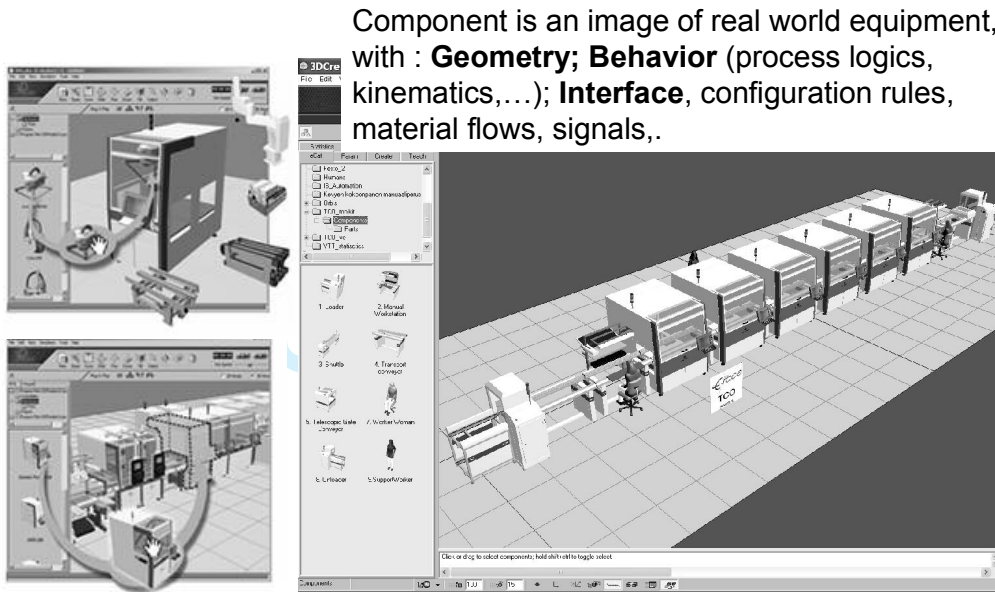


Figure 1: Component-based simulation is ideal for modular system design

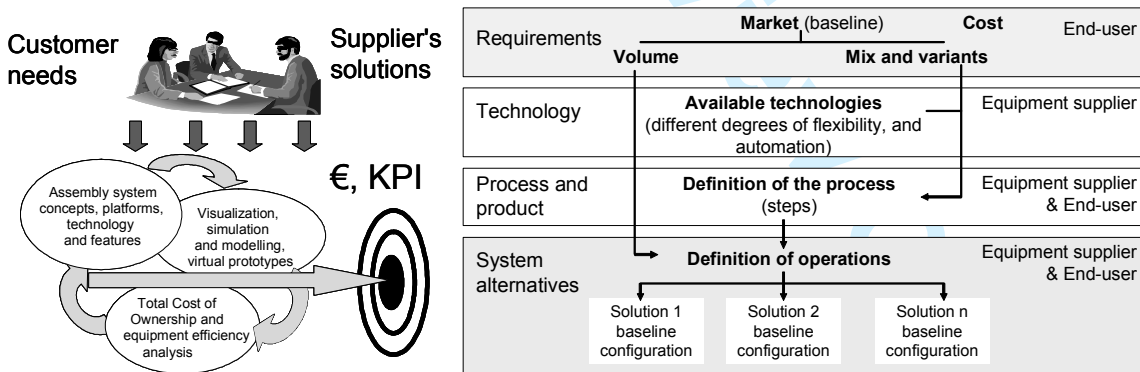


Figure 2: The development aims to improve design quality and communication.

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

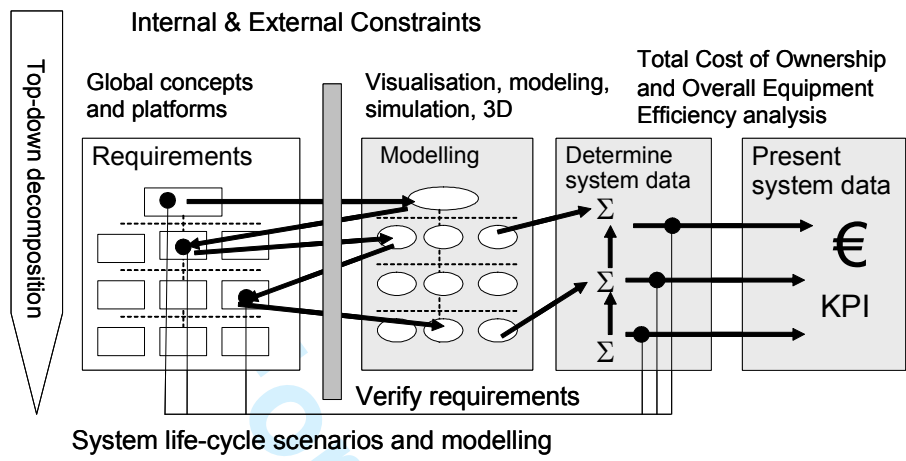


Figure 3: Form requirements to assembly system cost efficiency

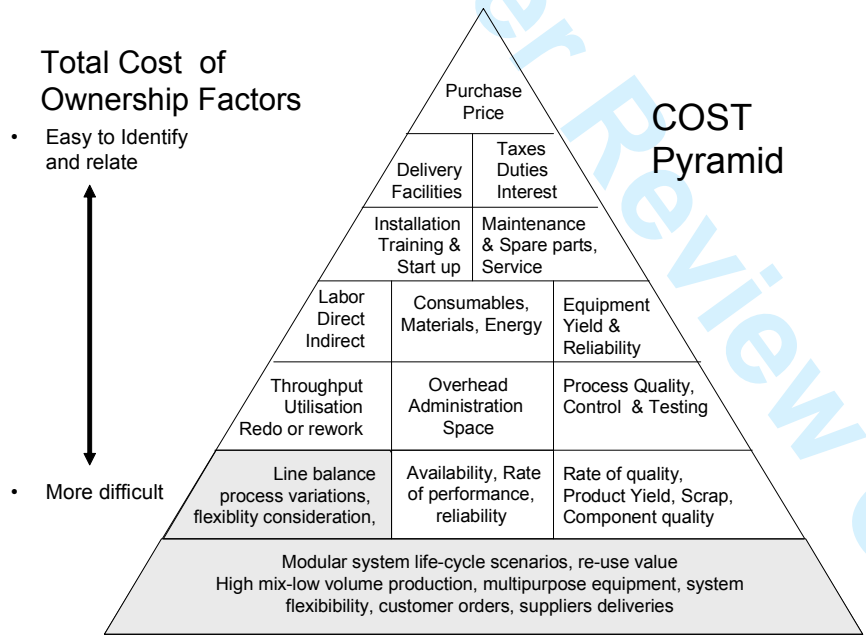


Figure 4: The Cost Pyramid modified from SEMI E35-0701.

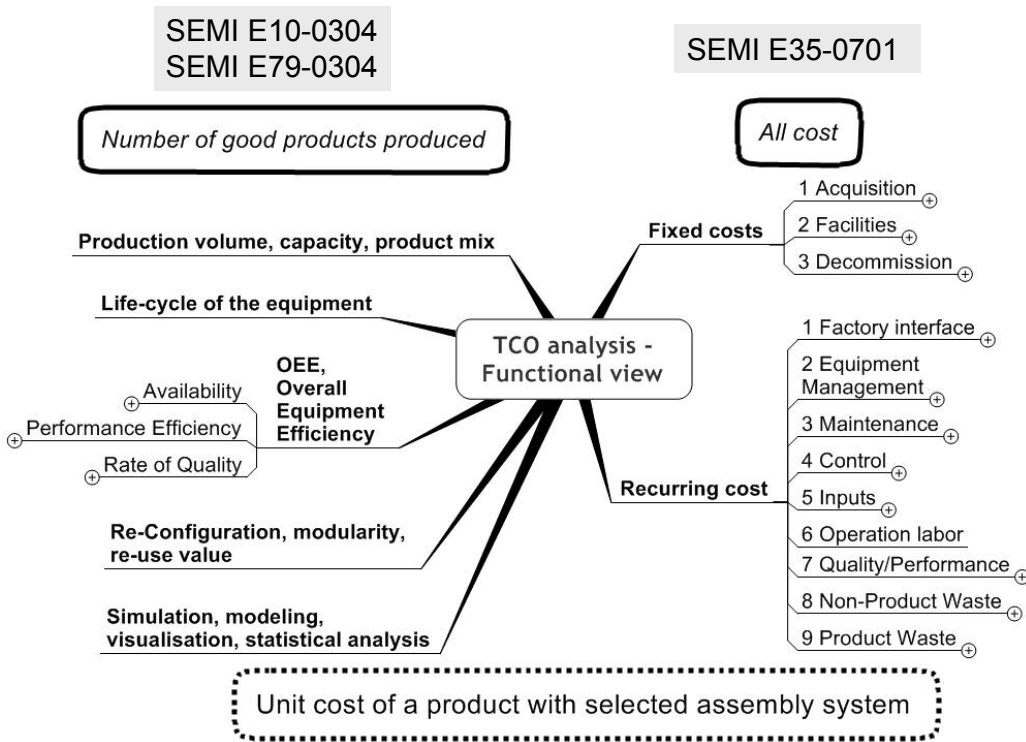


Figure 5. Methodology integration for E-Race TCO analysis toolkit

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

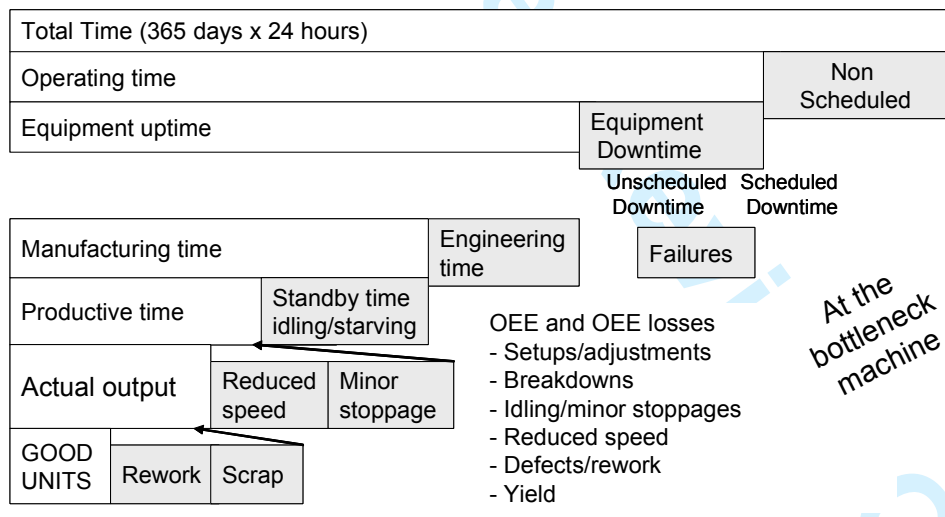
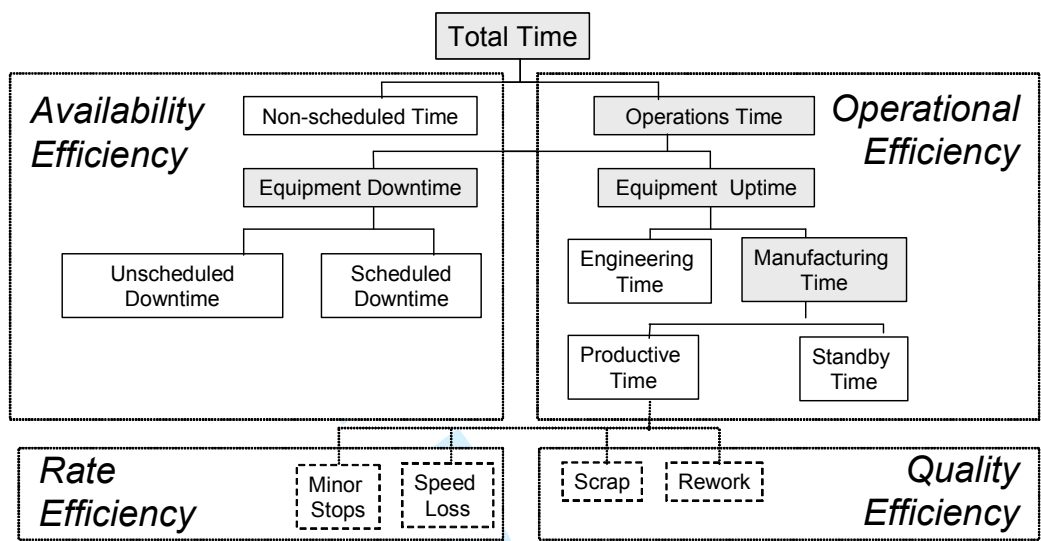


Figure 6: Classification of production time upper level.

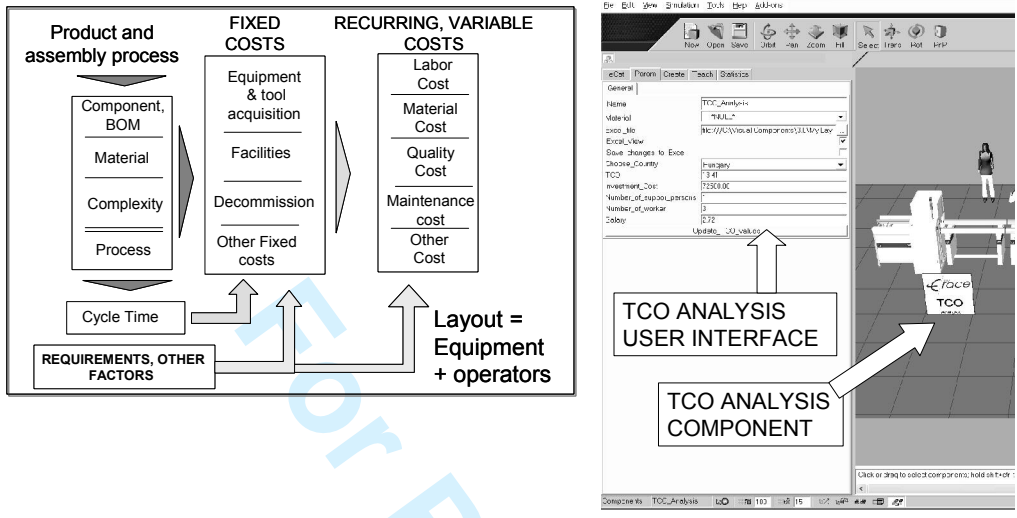


Figure 7. Using the TCO analysis component.

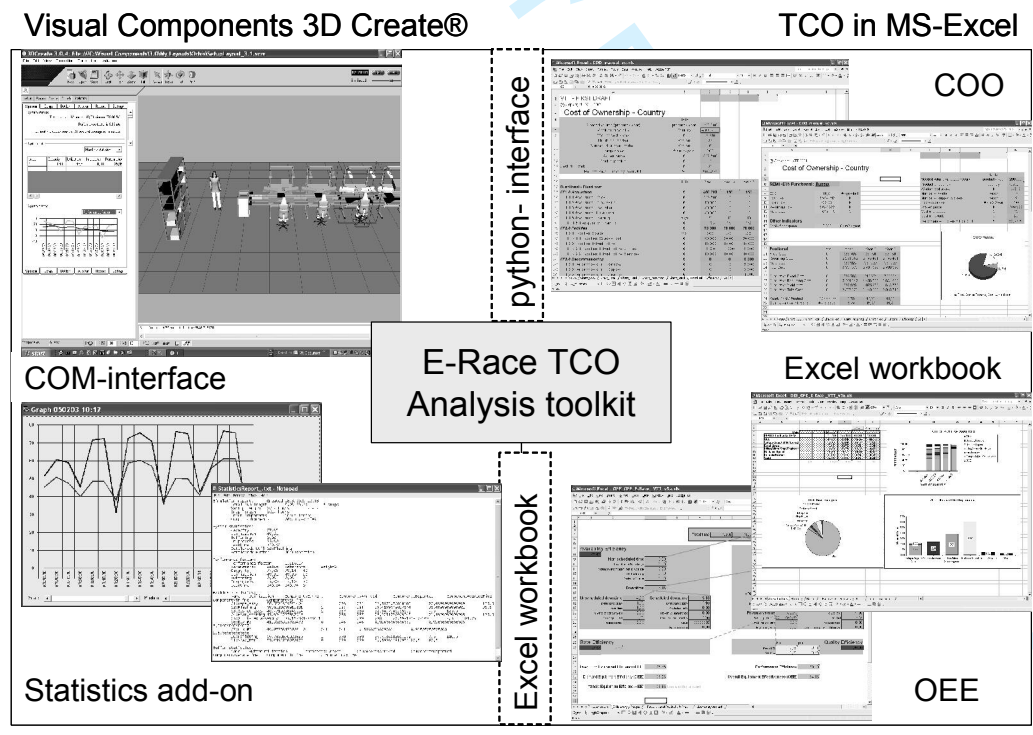


Figure 8. Overview of the TCO analysis toolkit.

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

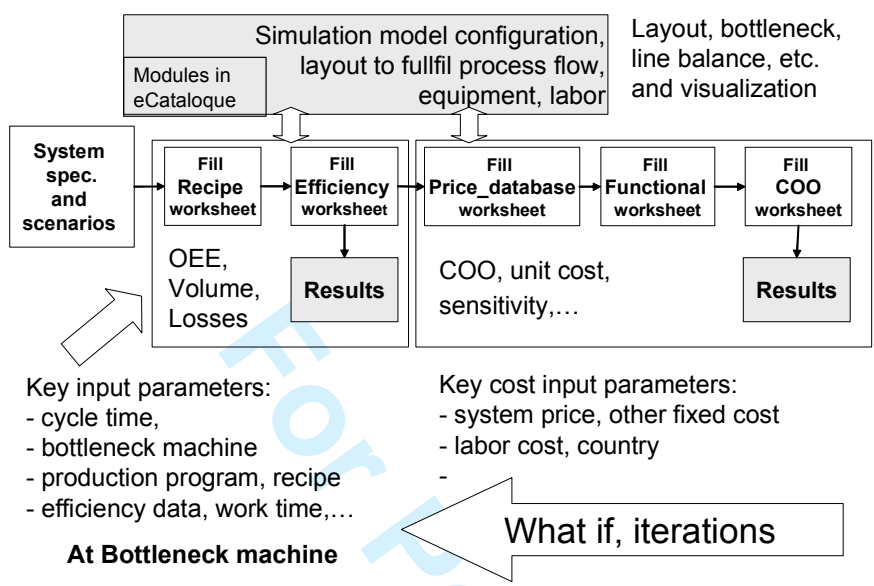


Figure 9. Analysis workflow, iterative steps not shown.

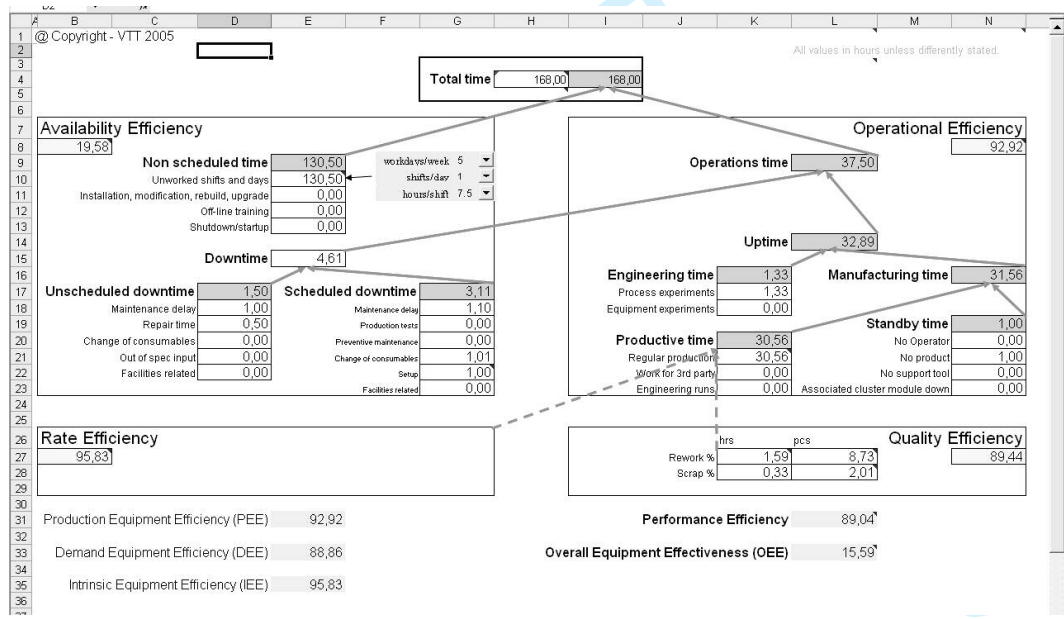
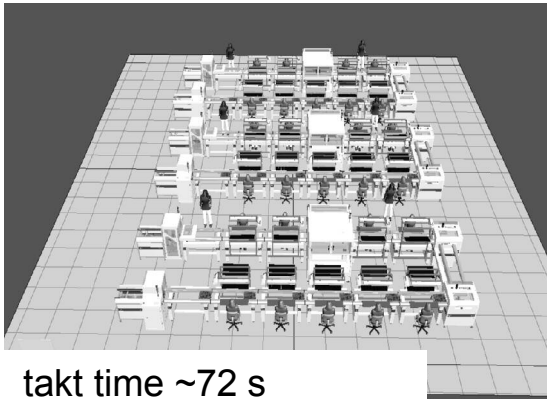
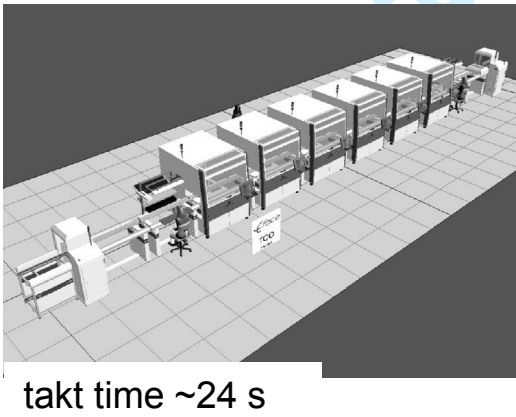


Figure 10. OEE data for 3-shift arrangement.



17
18
19
20
21
22

Figure 11: Semi-automated assembly lines.



38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

Figure 12: Automated assembly line.

Tables

Table 1. OEE Six big losses.

OEE efficiency calculations	Major OEE losses	Losses sub-category	SEMI E10 efficiency calculations
Availability	Set-ups/adjustments	Non-scheduled Preventative maintenance Qualifications	Non-scheduled time Scheduled downtime
	Breakdowns	Set-up Equipment failure Process failure Facility failure	Unscheduled downtime
Performance efficiency	Idling/minor stoppages	Engineering No product No operator Limited capacity	Engineering time Standby/idle time Other time losses Tool speed losses
	Reduced speed	Slow speed Stoppage/assist	Average batch size Productive
Rate of quality	Defects/rework Yield	Rework Scrap	Quality losses

Table 2. Fixed cost sub-classes, modified from SEMI E35-0701

Functional - Fixed cost	Units	Year 1	Year 2	...	Year n
F1.0 Acquisition	€				
F1.1 Acquisition: Price	€				
F1.2 Acquisition: Purchasing	€				
F1.3 Acquisition: Evaluation	€				
F1.4 Acquisition: Installation	€				
F1.5 Acquisition: Training	days				
F1.5.1 Acquisition: Training	€				
F2.0 Facilities	€				
F2.1 Facilities: Space	m ²				
F2.1.1 Facilities: Space - cost	€				
F2.2 Facilities: Infrastructure	€				
F2.2.1 Facilities: Infrastructure: Utilities	€				
F2.2.2 Facilities: Infrastructure: Services	€				
F3.0 Decommissioning	€				
F3.1 Decommissioning: Removal	€				
F3.2 Decommissioning: Disposal	€				
F3.3 Decommissioning: Cleanup	€				

Table 3. Recurring cost sub-classes, modified from SEMI E35-0701

Functional - Recurring cost	units	Year 1	Year 2		Year n
R1.0 Factory Interface	€				
R1.1 Factory Interface: Labour	Persons				
R1.1 Factory Interface: Labour – cost	€				
R1.2 Factory Interface: Safety	€				
R1.4 Factory Interface: Infrastructure	€				
R2.0 Equipment Management	€				
R2.1 Equipment Management: Supervision	Persons				
R2.1.1 Equipment Management: Supervision - cost	€				
R2.2 Equipment Management: Support	Persons				
R2.2.1 Equipment Management: Support - cost	€				
R2.3 Equipment Management: Administration	Persons				
R2.3.1 Equipment Management: Administration - cost	€				
R3.0 Maintenance	€				
R3.1 Maintenance: Service Contracts	€				
R3.2 Maintenance: Labour-Other	Persons				
R3.2.1 Maintenance: Labour-Other - cost	€				
R3.3 Maintenance: Spare Parts	€				
R3.4 Maintenance: Repair Parts	€				
R4.0 Control	€				
R4.1 Control: Software	€				
R4.2 Control: Training	Days*Person				
R4.2.1 Control: Training – cost	€				
R4.3 Control: Support	Days*Person				
R4.3.1 Control: Support - cost	€				
R4.4 Control: Backup	€				
R5.0 Inputs	€				
R5.1 Inputs: Consumables	€				
R5.2 Inputs: Material	€/product				
R5.2 Inputs: Material – cost	€				
R5.3 Inputs: Utilities	€				
R6.0 Operation Labour	€				
R6.0.1 Operation Labour	Persons				
R9.0 Product Waste	€				
R9.3 Scrap: Yield loss					
R9.3.1 Scrap: Yield loss - cost	€				
R9.4 Rework	nbr				
R9.4.1 Rework – cost	€				

Table 4. Table OEE, Volume and Loss Factors

Parameters	1 shift, S1	3 shifts, S3
workdays/week	5	5
shifts/day	1	3
shift length [hr]	7.5	7.5
Calculated volume, products/year	213 785	235 164
Overall Equipment Effectiveness (OEE), %	15.59	51.45
Performance Efficiency in OEE, %	89.04	91.26
Quality Efficiency in OEE, %	89.44	90.31
Availability Efficiency in OEE, %	19.58	62.43
Big losses		
Set-ups/Adjust./PM Non-scheduled.	79.53	34.89
Breakdowns	0.89	2.68
Idling/Minor Stop/Engineer	1.39	2.98
Reduced Speed	0.76	2.48
Defects/Rework	1.52	4.56
Yield	0.32	0.96

Table 5. Semi-automated lines input values for COO

Major input	Unit	Scenario ES L3S1	Scenario ES L1S32
Calculated volume (product / year)	product / year	213 785	235 164
Production country	Country	Russia	Russia
Worker cost per year	€	3 910	3 910
Number of workers	Person	27	9 x 3
Number of support workers	Person	6	2 x 3
System price	€	409 500	136 500

Table 6. Summary results for scenario ES L3S1, three lines in one shift.

Functional	Units	Year 1	Year 2	Year 3
Fixed Cost	€	544 119	71,209	71 209
Recurring Cost	€	2 414 690	2 414 284	2 414 284
Yield cost	€	22 947	22 947	22 947
Total Cost	€	2 981 756	2 508 440	2 508 440
Cumulative Fixed Cost	€	544 119	615 328	686 537
Cumulative Recurring Cost	€	2 414 690	4 828 974	7 243 258
Cumulative Yield cost	€	22 947	45 894	68 841
Cumulative Total Cost	€	2 981 756	5 490 196	7 998 636
Yearly Cost / Product	€ / product	13.947	11.733	11.733
Cumulative Cost / Product	€ / product	13.947	12.840	12.471

Table 7. Summary results for scenario ES L1S3, one line in three shifts.

Functional	Units	Year 1	Year 2	Year 3
Fixed Cost	€	209 694	50 734	50 734
Recurring Cost	€	2 576 820	2 576 414	2 576 414
Yield cost	€	23 136	23 136	23 136
Total Cost	€	2 809 649	2 650 283	2 650 283
Cumulative Fixed Cost	€	209 694	260 428	311 162
Cumulative Recurring Cost	€	2 576 820	5 153 233	7 729 647
Cumulative Yield cost	€	23 136	46 271	69 407
Cumulative Total Cost	€	2 809 649	5 459 933	8 110 216
Yearly Cost / Product	€ / product	11.948	11.270	11.270
Cumulative Cost / Product	€ / product	11.948	11.609	11.496

Table 8. Evaluation of concept scenarios

Results	Russia ES L1S3	Sweden WA L1S3	Sweden WS L1S3	Russia ES L3S1
COO, € / product	11.50	18.77	14.31	12.47
Total Cost [€]	8 110 216	13 239 864	9 177 761	7 998 636
Fixed Cost [€]	311 162	350 783	1 008 043	686 537
Recurring Cost [€]	7 729 647	12 819 674	8 100 877	7 243 258
Yield cost [€]	69 407	69 407	68 841	68 841
Overall Equipment Effectiveness (OEE), %	51.45	51.45	15.59	15.59
Performance Efficiency from OEE, %	91.26	91.26	89.04	89.04
Quality Efficiency from OEE, %	90.31	90.31	89.44	89.44
Availability Efficiency from OEE, %	62.43	62.43	19.58	19.58
Calculated volume (product / year)	235 164	235 164	213 785	213 785
Parameters				
Production country	Russia	Sweden	Sweden	Russia
Worker cost per year [€]	3 910	48 505	48 505	3 910
Number of workers	27	27	2	27
Number of support workers	6	6	1	6
System price [€]	136 500	136 500	643 000	409 500
Cost of product [€]	10.19	10.19	10.20	10.20
Cost of rework [€]	20.37	20.37	20.41	20.41
workdays/week	5	5	5	5
shifts/day	3	3	1	1
shift length [hr]	7.5	7.5	7.5	7.5