Modeling and Simulation for Decision Making in Sustainable and Resilient Assembly System Selection

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Abstract

Resiliency requires manufacturing system adaptability to internal and external changes, such as quick responses to customer needs, supply chain disruptions, and markets changes, while still controlling costs and quality. Sustainability requires simultaneous consideration of the economic, environmental, and social implications associated with the production and delivery of goods. Due to increasing complexity, the engineering of a production system is a knowledge-intensive process. In this paper, a summary of system adaptation methods are shown, and a holistic methodology for the assembly equipment and system modeling and evaluation is explained. The aim here is to bring resiliency and sustainability considerations into the early decision-making process. The methodology is based on estimations on system performance, using discrete event simulation run results, or other process modeling methods, and the use of Key Performance Indicators (KPI), such as Overall Equipment Efficiency (OEE), connected to cost parameters and environmental aspects analysis. Overall, it is a tool developed through multiple projects for design specification reviews and improvements, trade-off analysis, and investments justification.

Keywords: resilient assembly systems, sustainability, modeling and simulation, decision support

1 Introduction

Manufacturing has to cope with a continuously increasing variety of products, change of volumes, shortening product life cycles, and various disturbances. There has been a shift to the product personalization, customer and market responsive resilient manufacturing. Advanced manufacturing faces challenges: digitization, the shift towards more environmentally sustainable production and transition from Industry 4.0 towards Industry 5.0, and a sustainable, human-centric and resilient European industry (De Nul *et al.,* 2021).

Sustainability is an increasingly important driver. Sustainable Manufacturing has commonly used the following definition (US Department of Commerce, 2007): "*The creation of manufactured products that use processes that minimize negative environmental impacts, conserve energy and natural resources, are safe for employees, communities, and consumers and are economically sound*".

Resiliency is usually defined as the ability of a system to recover from an undesired state and to a desired state. A list of resiliency attributes and their impacts on manufacturing is provided in (Kusiak, 2019; 2020). They include *energy, materials, components, physical assets and processes, transport, supply chain, communications, logistics, efficiency, productivity, capacity, dependability, quality, compatibility, sustainability, workforce, and societal values.* These attributes can be expressed in different forms, metrics, and variables, some of which are measurable. Identification and definition of these variables is important for understanding the nature of manufacturing resiliency and sustainability.

Assembly is one of the last processes within a product realization, a manufacturing operation in which the components and subassemblies are integrated and joined together to get the final product. Resiliency requires system adaptability to internal and external disruptions and changes, e.g., machine setups and job rescheduling for quick responses to customer needs or missing material due to supply chain disturbances. There is a need for the holistic evaluation and decision support methodology in the engineering phase of production and assembly systems.

1.1 Aims

This paper briefly shows how to increase an assembly system resiliency, adaptability to changes in products, and production volumes. Solution is an agile, interoperable, reconfigurable modular system and processes with smart tools, technologies, digitalization, and empowered human operators.

This paper describes holistic methodology for assembly equipment and system evaluation, for design specification reviews and improvements, trade-off analysis, and investments justification. The aim is to bring resiliency and sustainability aspects to the early decision-making process: identify attributes, parameters, visualize, model, simulate, and calculate, in other words use advanced analytics techniques and use

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the created information to improve and make better decisions - "*resilience and sustainability-by-design*".

1.2 Sustainable manufacturing

The World Commission on Environment and Development (1987) defined "*Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs.*" This elaborated the meaning of sustainability and presented it in three dimensions, i.e., Environmental, Social, and Economic responsibilities, commonly known as the triple bottom line concept (Figure 1).

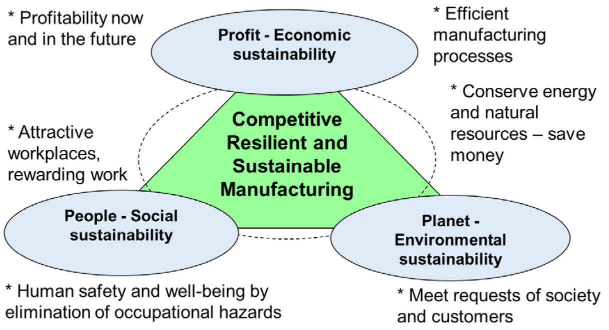


Figure 1. Triple bottom Line (TBL) and Competitive Resilient Sustainable Manufacturing.

The general principle of sustainable manufacturing is to reduce the intensity of materials use, energy consumption, emissions, and the creation of unwanted by-products while maintaining, or improving, the value of products to society and to organizations. Enhancing sustainability performance of the production process is an important contribution to developing a stronger and cleaner economy.

1.3 Resilient and Agile Manufacturing

Resilient Manufacturing is defined as *the ability of a manufacturing system to efficiently mitigate any external disruptions, either derived from the supply chain of the company or resulted from the volatility of the market demand.* Further, the response of the system to these volatile changes must be as rapid as possible in order for the company to maintain their competitive advantage in the market landscape (Mourtzis *et al.*, 2021; Kusiak, 2019).

Resilient manufacturing has similarities to agile and reconfigurable manufacturing. The goal of agile manufacturing is to combine the organizations, people and, technology into an integrated and coordinated whole (Dove 1992; Kidd 1994; Heilala and Voho, 2001). Agility is defined as "*the capability of surviving and prospering in a competitive environment of continuous and unpredictable change by reacting quickly and effectively to changing markets, driven by customer-designed products and services*". Agile manufacturing utilizes effective interoperable systems, process tools, modular reconfigurable systems, human resources, and training to enable manufacturing systems and networks to respond quickly to customer needs and markets changes while still controlling costs and quality (Dove, 1992).

1.4 Requirements and solutions

Flexibility requirements can be classified to static flexibility, where reaction time is typically connected to the planned product life-cycle phases, e.g., production volume changes, new variants, or products in the same system. In dynamic flexibility, reaction time is very short due to customization, lot size one, assembly-to-order, disturbances, machine breaks, repair work, rush orders, and demand fluctuations. Solutions can be physical adaptation on hardware, equipment level or logical, adaptation with software, change of programs, re-planning, re-routing etc. as shown in Table 1.

Table 1. Flexibility solutions adapted from (Heilala and Voho, 2001)

Static flexibility, physical "hardware"	*Dynamic flexibility, logical "programs"*
▪ Layout physical modifications ▪ Level of automation ▪ Re-configurability, re-utilization ▪ Modularity, expandability ▪ Scalable ▪ Exchange of system modules or submodules	▪ Control of tasks and resource settings ▪ Use of information technology ▪ Change of control programs, routines ▪ Robotics, flexible automation, ▪ Human intelligence and skills ▪ Sorting and routing of material and order flow

Technical solutions concepts, e.g., re-configurability at hardware and software defines the capability window of the system (Table 1). System capacity, production volume, can be adapted by increasing work time, e.g., more shifts, increased level of automation, or by adding more resources. Flexibility also depends on logistics and material flow. In a modern supply chain, production network and adaptation can also be done at different organizational levels, e.g., re-routing and re-scheduling can include external suppliers of the network. Requirements for the factory automation are shown by Dotoli *et al.* (2019) and requirements for the smart factory system by Ambkhot *et al.* (2018) and Kusiak (2019). Challenges for the Cyber Physical Production Systems (CPPS), requirements for manufacturing and key success factors for next generation manufacturing are shown by Panetto *et al.* (2019). Findings are similar to (Heilala and Voho, 2001) earlier, with a note that technology has evolved due to the introduction of Industry 4.0, Industrial Internet of Things (IIoT).

Drivers for resilient sustainable manufacturing can be listed as follows:

- Increase operational efficiency by reducing costs and waste;
- Respond to or reach new customers and increase competitive advantage;
- Build long-term business viability and success;
- Protect and strengthen brand and reputation and build public trust;
- Respond to regulatory constraints and opportunities;
- Provide a healthy workplace and empower the workforce; and
- Minimal use of natural resources while reducing environmental impact.

2 Design, modeling and evaluation

Resiliency and agility are about the system and process adaptation to the planned changes and unplanned disturbances. The design of an adaptable manufacturing system involves a number of interrelated subjects, such as tooling strategy, material-handling methods, system size, process and material flow configuration, flexibility needed for future engineering changes, production methods, capacity adjustment, and production floor layout strategy. Sustainable manufacturing system design takes into account the social, economic, and ecological constraints as well.

For analyzing environmental sustainability earlier in the product lifecycle, Brundage *et al.* (2016) suggest use of the SIMA reference model. SIMA, Systems Integration of Manufacturing Applications, reference architecture, developed at NIST (Barkmeyer *et al.,* 1996), addresses product design engineering, manufacturing engineering, production systems engineering, and production activities corresponding to the four top-level activities: (A1) Design Product, (A2) Engineer Manufacture of Product, (A3) Engineer Production System, and (A4) Develop Products (Figure 2).

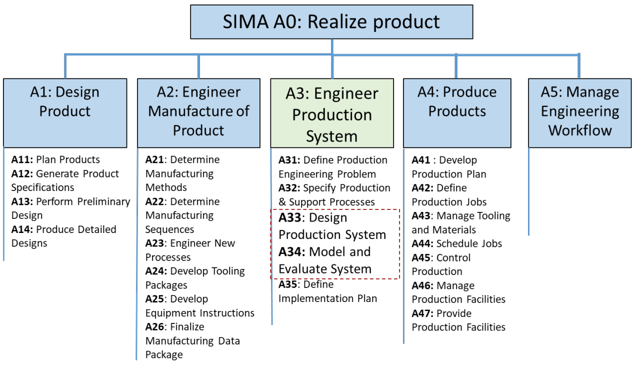


Figure 2. SIMA activities reference model adapted from (Barkmeyer *et al.*, 1996).

SIMA provides the structure of the product realization process. This paper is focused on the A3 Engineering of Production System, specifically to sub phases *(A33) Design Production System and (A34) Model and Evaluate System.* Production systems encompass processes, activities, and includes the resources and controls for carrying out the processes. Process design defines what is being performed in the system. The system design phase emphasis is on details of how, where, and when the process is performed (Phase A33 in Figure 2). In this phase, requirements, needs, strategies, market forecast and product structure, bill of material, production, and auxiliary process are known.

Based on requirements and potential solution designs, life-cycle scenarios are modeled and evaluated (Phase A34 in Figure 2). This can be an iterative process, as shown in Figure 3. The aim is justification of investment into potentially more expensive flexible equipment having a higher re-use value and longer life-time, better adaptation to changes, and/or brings other value, e.g., higher quality rate, and human and environmental aspects.

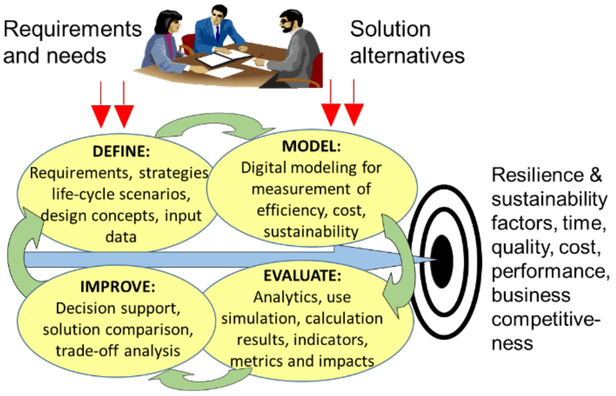


Figure 3. Methodology overview.

2.1 Define requirements and needs

The starting point is strategies, requirements, and needs, e.g., system lifetime scenarios, current and future product mix, and volume estimations. Modular structure of the production system enables use of the unit manufacturing process (UMP) model, as shown in Figure 4.

Product and process information, product structure, bill of material (BOM), production, and auxiliary processes are parameters to the system design. Each of the manufacturing process unit has planned input and output, resources, product and process information, see Figure 4.

In the definition phase, the cost parameters related to inputs are as follows: energy, materials and consumables, and resources: equipment, tools, fixtures, and human operators are identified. The amount of inputs, resource usage, and outputs can be calculated using static process modeling data or using dynamic simulation run results, as shown in the following chapters in this paper.

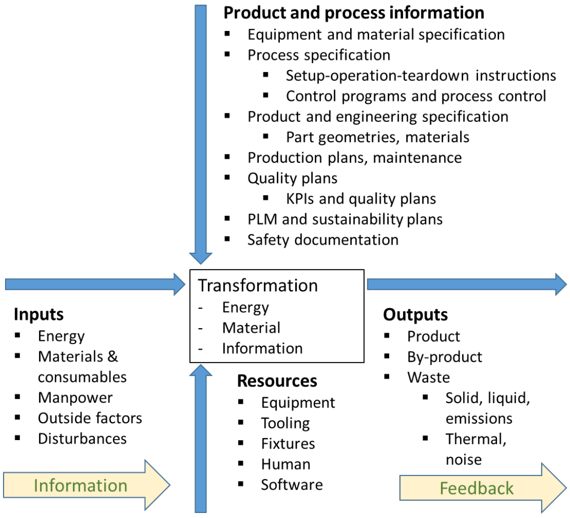


Figure 4. At system- and each module-level information (adapted from ASTM E3012 standard; Mani *et al.* 2016).

2.2 Solution modeling

There are several methods for manufacturing system modeling: analytic, symbolic, and models capturing the dynamics of the systems.

Analytic models, such as mathematical formulas, queue formulas, and linear programming, can give a quick answer. Some are able to give an optimum solution without going through trial and error. Their disadvantages include simplified assumptions that are often unable to account for random behaviors and, thus, a simplified solution to complicated problems.

Symbolic models, such as process flow diagrams, flowcharting, and Integrated DEFinition (IDEF), are suitable for communication, easy to understand, and quick to develop. The focus on the processes in the system are not aimed to resolve resource issues and operational problems too early. The disadvantages include lack of details, little or no quantitative measure of system elements or description of elements, activities, and relationships, and failure to capture the system dynamics. Symbolic models are static models.

Factory simulation measures the effects of process variability and interdependencies on overall system performance. A simulation creates an artificial history of the system. The disadvantages are that models can be difficult to construct – model building can be time-consuming and challenging.

In principle, a combination of the above-mentioned methods should aid engineers in speeding up the design process and improve decision making (Paju *et al.*, 2010). Analytic models in spreadsheets are commonly used by engineers and can be connected to symbolic, static and factory simulation models. Simulation models can read and write to external software, e.g., spreadsheets.

2.2.1 Manufacturing system modeling

Value Stream Mapping (VSM) is a simple-to-use symbolic process-modeling tool (see Figure 5**)**. It specifies the activities, cycle times, down-times, and delays, and identifies bottlenecks and non-value-added activities in the production or in the logistics. A snapshot of the process activities in production may be created based on average data. Conventional VSM can be created for one product or product family with a pen and paper, although there are numerous VSM software tools. Combining VSM or similar process modeling to spreadsheets, an engineer can make an estimation of production mix and volumes.

VSM and environmental analysis have merged together in some applications. The US Environmental Protection Agency (EPA) has introduced the Lean and Environment toolkit, which offers practical techniques and strategies for environmentally protective lean decision making (EPA 2007).

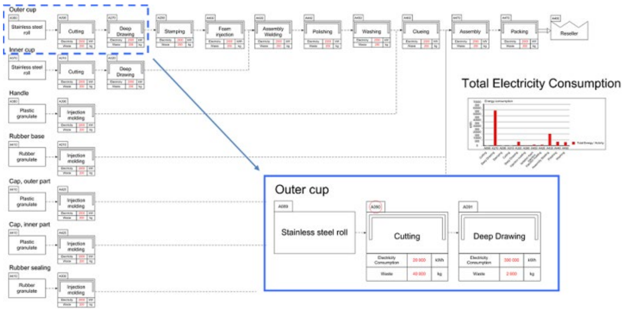


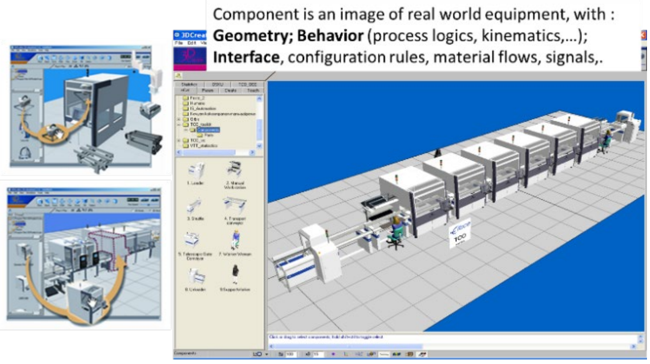
Figure 5. Example of VSM model adapted from (Paju *et al.,* 2010**).**

Discrete Event Simulation (DES), a factory simulation, allows the experimentation and validation of different products, processes, and manufacturing system configurations (Mourtzis *et al.,* 2018). The simulation model is the virtual image of the planned real system. Discrete event/material flow/factory simulation is used in the design phase to evaluate concepts and optimize system solutions before investments and strategic decisions are made.

The common aim in simulation studies is to identify problem areas, and to quantify or optimize production system performance, such as throughput under average and peak loads, the utilization of resources, labor and machinery, staffing requirements, work shifts, bottlenecks, choke points, queuing at work locations, queuing caused by material handling devices and systems, the effectiveness of the scheduling system, the routing of material, the work in process, and storage needs.

The modular system structure can be implemented to layout planning and modeling systems. For example, in the assembly system layout configuration, model building, using 3D pre-defined and parametric sub-module merging, enables fast scenario creation (Heilala *et al.,* 1998; 2007; 2008a). In some cases, a standardized, parametric simulation submodule, catalogue equipment item can be shared on the internet, e.g., Visual Components public web eCatalog (Visual Components

2021). There are many other factory simulation tools in the market, supporting submodule merging.



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

Figure 6. Component-based simulation adapted from (Heilala *et al.*, 2008a).

Modeling modularity is feasible on workstation and at sub-module, e.g. material feeding, jigs, fixtures and tool level as shown in Figure 6. Parametric modeling enables fast model changes. Environmental aspects can also be included in the production simulation analysis, as shown in later in Figure 9 . The environmental aspect analysis with DES or VSM adds the complexity in the input data collection since more data is needed. VSM model parameters and DES simulation run results can be further analyzed in spreadsheet tools, e.g., excel.

2.3 Evaluation and analytics

Modeling for analytics needs a resource, bill of material and product route data, process, order, production schedule, volume, mix, and data for system availability, set-ups, planned maintenance, reliability, machine breaks, and estimated production quality rate data, e.g., yield, rejects, scrap and rework. Use of the UMP model (see Figure 4) enables structure for data collection for each manufacturing unit, and these units can be modeled with VSM or DES, including connection between those units.

The output of analytics is equipment operation data and the percentages of machine statuses (on, off, stand by, under repair), thus allowing the amount of energy needed to be calculated. Using capacity data, we are able to calculate factors such as the piece count and material used during operations. DES shows the dynamics of the system. In Value Stream Mapping (VSM) and combined spreadsheet calculation, production volume data is deterministic, based on static, average data.

2.3.1 Cost and efficiency aspects analytics

Looking at system, equipment, or service purchase price is not enough. Life Cycle Cost (LCC) or Total Cost of Ownership (TCO) is the purchase price of a product or service plus the costs of operation throughput its life cycle. Cost of ownership (COO), as defined by SEMI standards, goes deeper (SEMI E35, SEMI E10, SEMI E79), looking also on profitability, COO of good units. COO depends on the production throughput rate, equipment acquisition cost, equipment reliability, throughput, yield, and equipment utilization, see Figures 7 and 8.

The basic COO is given by the following equation. COO per good unit equals all costs divided by total number of good products during the lifetime of the equipment

$$\mathrm{COO}_{\text{per good unit}} = \frac{\text{Total costs}}{\text{Good units}} = \frac{FC + VC + YC}{L \times THP \times U \times Y} \qquad (1)$$

where

FC = Fixed costs (amortized for the period under consideration), Acquisition, installation, training, etc.

VC = Operating costs (variable or recurring costs), factory interface, management, maintenance, control, materials, energy, labor costs, etc.

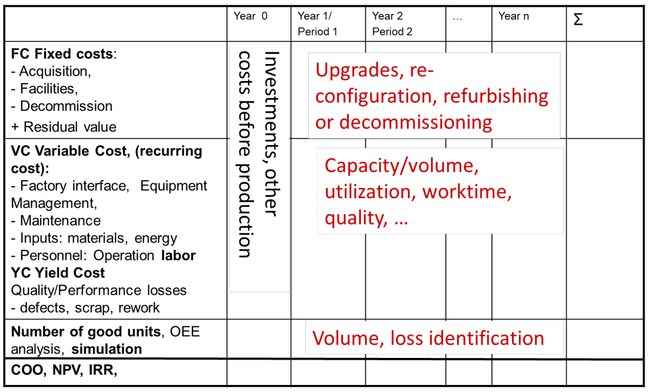
YC = Yield loss costs, scrap, rework,

L = Life time of equipment

THP = Throughput rate (nominal)

U = Utilization

Y = Yield



	Year 0	Year 1/ Period 1	Year 2 Period 2	…	Year n	Σ
FC Fixed costs: - Acquisition, - Facilities, - Decommission + Residual value	Investments, other costs before production	Upgrades, re-configuration, refurbishing or decommissioning				
VC Variable Cost, (recurring cost): - Factory interface, Equipment Management, - Maintenance - Inputs: materials, energy - Personnel: Operation **labor** **YC Yield Cost** Quality/Performance losses - defects, scrap, rework		Capacity/volume, utilization, worktime, quality, …				
Number of good units, OEE analysis, **simulation**		Volume, loss identification				
COO, NPV, IRR,						

Figure 7. Life cycle cost (LCC), time-based matrix.

Yield loss cost is a measure of the value of units lost through bad quality (e.g., misprocessing, defects) and is broken out separately to demonstrate the importance of yield to both the numerator and denominator. The cost of lost yield increases, if the component travels forward in the processes before detecting the error. Some cost factors are more difficult than others to accurately determine in the concept phase.

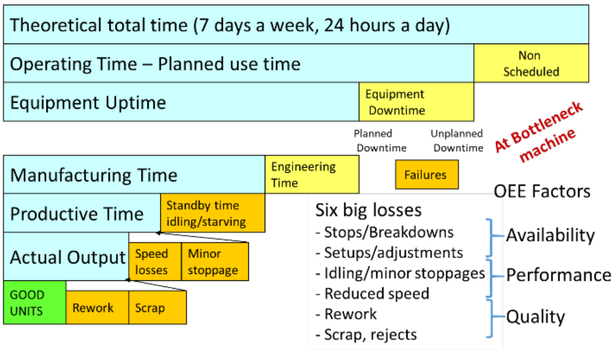


Figure 8. OEE time classification and six big losses.

The number of good products depends on reliability, availability, and maintainability (RAM) and utilization of equipment in a manufacturing environment. OEE (Overall Equipment Efficiency/Effectiveness) is an all-inclusive metric of equipment productivity, i.e., it is based on reliability, (Mean Time Between Failures-MTBF), maintainability (Mean Time To Repair-MTTR), utilization (availability), throughput, and yield.

All of the above factors are grouped into the following three sub-metrics of equipment efficiency.

1. Availability
2. Performance efficiency
3. Rate of quality

The three sub-metrics and OEE are mathematically related as follows: OEE % = Availability x Performance Efficiency x Rate of Quality x 100

OEE is a systematic way to evaluate production losses, normally used as an equipment key performance indicator (KPI). It helps to identify the actual time the system is producing good units, and at the same time it identifies and evaluates the OEE losses, like setups/adjustments, breakdowns, idling/minor stoppages, reduced speed, defects/rework (see Figure 8). In production systems, typically the focus is on the bottleneck machine. In the case of high mix, low volume production, the bottleneck location varies depending on customer orders and workload.

In the case of the DES model, with detailed input data, including data on MTBF, MTTR, cycle time variations, and material flow disturbances, it is possible to define the OEE based on simulation run results. In the case of using the VSM model and spreadsheet analytics, engineers can define the estimated OEE values themselves, by identifying six big losses shown in Figure 8.

In the design review or system sales negotiation phases, it is an advantage to identify potential OEE losses together with the customer, equipment or system user. Thus, there will be fewer surprises during the system utilization phase.

2.3.2 Environmental aspects analytics

VSM and DES are commonly used for manufacturing system analysis and development as shown earlier. Normally, these methods show selected production efficiency key performance indicators. At the same time, both methods create information about the production parameters needed for the calculation and analysis of environmental aspects (see Figure 9.).

Both VSM and DES can provide bookkeeping of production volume, number of products manufactured, cycle time, utilization, and equipment running time (Paju *et al.,* 2010).

Adding environmental data to process and equipment descriptions and planned production rate creates understanding of energy usage, greenhouse gas (GHG) emissions, usage of hazardous materials, waste, emissions, and so on. Usage can be shown per product, resource or process based on piece count or time period. This enables engineers to focus on the most harmful processes and optimize them.

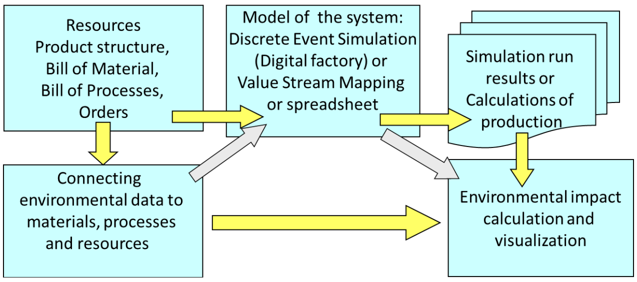


Figure 9. Environmental data connection to production resources, process, and product data.

An example of the categorization of sustainability performance indicators in manufacturing are shown in Figure 10. For air emission, e.g., carbon footprint analysis, the type and amount of material in kg, or energy usage in kWh, is just the starting point. There is a need to know the source of the raw material. Regarding energy, the CO2 emission using fossil fuels is much higher compared to renewal energy sources, e.g., water, wind, or solar energy.

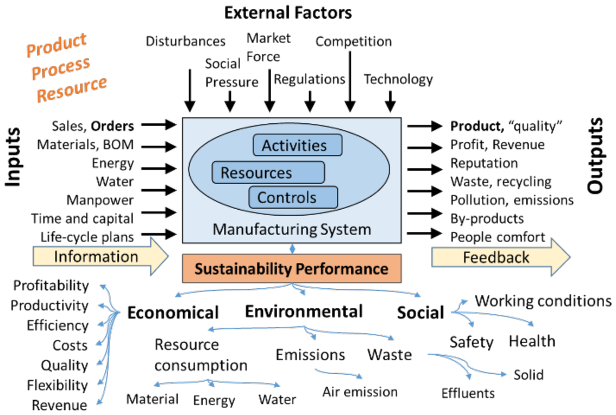


Figure 10. Typical manufacturing sustainability performance indicator adapted from (Beltrami *et al.,* 2021).

With the BOM, environmental data from cradle to the factory gate can be taken from the public LCI data sets, e.g., European Reference Life Cycle Database (ELCD3) (European Commission LCI 2018), or by using commercial data bases.

2.4 Improve decision making

Simulation studies, modeling parameters, input data, and run results, or other modeling methods combined with other relevant information, do provide data for analytics. Decision makers, managers, and development engineers are interested in planned system cost efficiency, investment and operating costs, productivity, throughput, utilization, availability, quality rate, flexibility, and all sustainability performance aspects.

Social sustainability is measuring working conditions, occupational health, and safety. Environmental sustainability is measuring resource consumption, emissions, and waste. Beltrami et al. (2021) show the linkage of industry 4.0 technology and sustainability performance indicators, see Figure 10. The global standards for sustainability reporting (GRI 2020) are one source for defining sustainability indicators.

Environmental aspects are getting more important due to increasing regulation, and they are useful in marketing, in creation of brand, and reputation of the company. Evaluation can be an iterative process, managers and engineers can edit models, and model parameters for optimization, as well as for risk management (Figure 3).

3 Discussion

The presented methodology has evolved during a series of research projects starting in the mid-1990s. The human-friendly agile assembly system concept and modeling methods for modular assembly equipment started in the late 1990s (Heilala and Montonen, 1998; Heilala and Voho, 2001). The cost aspect with performance analytics were introduced in the early 2000s, starting with spreadsheet analytics, later some integration to commercial simulation software (Heilala *et al.,* 2007; 2008a). The development initiated from systems end-user flexibility needs as well as on assembly system vendor ongoing development efforts. Later, the environmental aspects were added, starting with energy consumption and the eco-engineering process during the 2010s (Heilala *et al.,* 2008b; Lind *et al.,* 2009; Paju *et al.,* 2010). This also shows how industrial needs have change, from cost-efficiency-dominant decision making to all sustainability aspects.

The presented methodology usage is not limited to assembly system evaluation, as shown in (Heilala *et al.,* 2007; 2008a; 2008b); in general, the presented principle can be adapted to advanced manufacturing systems development and investment evaluation. Managers and engineers can justify investments to adaptive, human- and environmentally friendly technologies, equipment, and processes. For example, COO analyzes the cost of ergonomics solutions, the physical and cognitive level of automation, and with the OEE evaluation of impact to productivity, benefits of investments can be estimated. It should be noted that in both COO and OEE analyses in spreadsheet tools, it could be for relative comparison, i.e., before versus after change or between competitive solutions. Using these metrics as relative measures, the modeler is not required to build the perfect model or obtain all possible data. In one case, analysis and modeling with normal office tools and advanced spreadsheet calculation were sufficient, e.g., the study on Augmented Reality usage in assembly, shown in (Sääski *et al.,* 2008). In that particular case, laboratory test set-up provided input data for analysis.

This presented methodology is not yet an integrated tool package. It is merely a conceptual methodology. Parts of methodology have been tested in the past in industrial-driven projects, and the results are published. The presented COO and OEE are based on SEMI standards SEMI E35-0305, SEMI E10-0304, and SEMI E79-0304, and these standards have been updated. The next steps would be to adapt to evolving standardization: e.g., ISO - International Organization for Standardization (https://www.iso.org/home.html), SEMI - the global trade association of electronics manufacturing supply chain (https://www.semi.org/en), VDMA - Association of mechanical and plan engineers (https://www.vdma.org/), VDI – The Association of German Engineers (https://www.vdi.de/en/home), ASTM International (https://www.astm.org/), see also (Mani *et al.,* 2016) - just to mention some standardization bodies working on relevant standardization.

4 Conclusions

A resilient system needs agility, re-configurability at various levels, resource and process modularity, re-usability, digitalization, and human and environmental friendliness. One challenge for the manufacturing industry is justification for such equipment, system, or service. The presented methodology is an attempt to improve the decision-making process with modeling and simulation. Currently, the presented methodology is a combination of dynamic analytics, e.g., the use of Discrete Event Simulation (DES) if feasible, combined with selected static modeling and calculation methods in a spreadsheet. Decomposition of aspects under study is the key in analytics.

All sustainability aspects are covered. Social sustainability, human safety, well-being, ergonomics solutions, and related investments, e.g., adjustable worktables, collaborative automation, both physical and cognitive technologies for enhancement, and augmenting human worker performance can be estimated. Economic sustainability, profitability, and efficiency connect the cost parameters of technology, process, or services and evaluate the impact on productivity. Environmental sustainability is looking at environmental impacts as well resource efficiency.

From a cost point of view, the purchase cost of equipment is not enough: evaluate all cost items, fixed and recurring costs, cost of poor quality, cost related to potential upgrades during life-cycle scenarios of the system. The presented cost calculation, Cost of Ownership (COO), also provides data for commonly used investment evaluation methods, and discounted cash flow techniques: Net Present Value (NPV) and Internal Rate of Return (IRR), see Figure 7.

From the production performance point of view, nominal system capacity and throughput are not enough: evaluate disruptive events, such as machine testing, set-ups, planned and unplanned maintenance, quality failures, missing parts, operators, or orders. These events, six big losses (see Figure 8), could lead to full or partial loss of production in the system. Therefore, gaining a fundamental understanding and evaluation of these events and associated impacts on system performance in the design phase will have a significant impact on the economic sustainability.

Environmental aspects can be estimated based on simulation run results or by using (VSM) methodology and spreadsheet calculations for equipment operation hours and the number of products (see Figure 9). Adding environmental data to process and equipment descriptions creates understanding of the energy usage pattern and related CO2 emissions, usage of hazardous materials, chemicals, estimates of the amounts of waste, bi-products, etc. The methodology is not a full Life Cycle Assessment (LCA) but provides data for doing the LCA.

Manufacturing is moving away from the dominating economic paradigm of "maximum gain with minimum capital investment" towards a more sustainable paradigm of "maximum added value using minimal resources and carbon neutrality".

The presented methodology is versatile, a solution-relative comparison without a perfect model, even with normal office tools. Symbolic models, even just with pen and paper, improve communications between stakeholders. Use of dynamic simulation models increases the accuracy of analytics as well complexity in model building.

The presented methodology measures selected resilience and sustainability aspects, to the organization over the planned life cycle of a piece of production equipment - not absolute accurate values in the concept creation phase - but data for comparison. The analytics is as good as input data is; input of false information does not produce the right results. The user should make a risk assessment of results, e.g., use of min, max, and optimal data values in calculation and simulations. The challenges are on getting reliable data in the conceptual phase.

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References

ASTM E3012-20, Standard Guide for Characterizing Environmental Aspects of Manufacturing Processes, *ASTM International*, West Conshohocken, PA, USA. 2020. doi:10.1520/E3012-20

E. Barkmeyer, N. Christopher, S. Feng, J. Fowler, S. Frechette, A. Jones, K. Jurrens, C. McLean, M. Pratt, H. Scott, M. Senehi, R. Sriram and E. Wallace. SIMA Reference Architecture Part I: Activity Models, NIST Interagency/Internal Report (NISTIR), *National Institute of Standards and Technology,* Gaithersburg, MD, USA, 1996. doi:10.6028/NIST.IR.5939

M. Beltrami, G. Orzes, J. Sarkis, and M. Sartor. Industry 4.0 and sustainability: Towards conceptualization and theory. *Journal of Cleaner Production*, Volume 312, 2021, 127733, ISSN 0959-6526, 2021. doi:10.1016/j.jclepro.2021.127733.

M. Brundage, W. Bernstein, T. Kliks, H. Nishi, S. Hoffenson, Q. Chang and K. Morris. Analyzing environmental sustainability methods for use earlier in the product lifecycle. *Journal of Cleaner Production*, 187: 877-892, 2018. doi:10.1016/j.jclepro.2018.03.187

L. De Nul, M. Breque and A. Petridis. Industry 5.0. Towards a sustainable, human-centric and resilient European industry. *European Commission,* 2021. doi:10.2777/308407

M. Dotoli, A. Fay, M. Miśkowicz, and C. Seatzu. An overview of current technologies and emerging trends in factory automation. *International Journal of Production Research,* 57(15-16): 5047-5067, 2019. doi:10.1080/00207543.2018.1510558

R. Dove. What Is All This Talk About Agility - The 21st Century Manufacturing Enterprise Strategy, *Japan Management Association Research,* Prevision, 1992.

EPA (2007). The Lean and Environment Toolkit. *U.S. Environmental Protection Agency.* https://www.epa.gov/sustainability/lean-environment-toolkit [Accessed July 1 2021].

European Commission LCI. (2018). ELCD 3. Life Cycle Inventory (LCI) data sets. Available via https://eplca.jrc.ec.europa.eu/ELCD3/ [Accessed June 17, 2021].

GRI. *Global Reporting Initiative standards*, 2020. https://www.globalreporting.org/standards. [Accessed 1 July 2021].

J. Heilala and J. Montonen. Simulation-based design of modular assembly system - use of simulation module library. In *Proceedings of 3rd EUROSIM Congress on Modelling and Simulation,* April 14-15, 1998. Helsinki, Finland, pages 493-498. ARGESIM Report 9, 1998. ISBN 978-3-901608-03-2.

J. Heilala and P. Voho. Modular reconfigurable flexible final assembly systems. *Assembly Automation*, 21(1): 20-30, 2001. doi:10.1108/01445150110381646

J. Heilala, O. Väätäinen, J. Montonen, T. Laaksonen and H. Kulmala. Decision Support and Simulation Methods for Assembly System Sales Engineers. In *Proceedings of the 6th EUROSIM Congress*, Ljubljana, Slovenia. 9-13 Sept. 2007. ARGESIM, 2007. ISBN 978-3-901608-32-2.

J. Heilala, J. Montonen and O. Väätäinen. Life cycle and unit-cost analysis for modular reconfigurable flexible light assembly systems. In *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture. Professional Engineering Publishing Ltd.,* Vol. 222, pages 1289 – 1299. 2008a doi:10.1243/09544054JEM1034

J. Heilala, S. Vatanen, J. Montonen, H. Tonteri, B. Johansson, J. Stahre, and S. Lind. Simulation-Based Sustainable Manufacturing System Design. In *Proceedings of the 2008 Winter Simulation Conference.* pages 1922-1930. 2008b doi:10.1109/WSC.2008.4736284

P.T. Kidd. Agile Manufacturing. Forming New Frontiers, *Addison-Wesley Publishing Company Inc.*, 1994. ISBN 0-201-63163-6.

A. Kusiak. Fundamentals of smart manufacturing: A multithread perspective. *IFAC Annual Reviews in Control,* 47: 214–220. 2019. doi:10.1016/j.arcontrol.2019.02.001

A. Kusiak. Resilient manufacturing. *Journal of Intelligent Manufacturing,* 31: 269, 2020. doi:10.1007/s10845-019-01523-7

S. Lind, B. Johansson, J. Stahre, C. Berlin, Å. Fasth, J. Heilala, K. Helin, S. Kiviranta, B. Krassi, J. Montonen, H. Tonteri, S. Vatanen, and J. Viitaniemi. SIMTER - A Joint Simulation Tool for Production Development. Espoo, VTT. 49 p. *VTT Working Papers*; 125. 2009. ISBN 978-951-38-7185-7

M.M. Mabkhot, A.M. Al-Ahmari, B. Salah, and H. Alkhalefah. Requirements of the Smart Factory System: A Survey and Perspective. *Machines* 2018, 6, 23, 2018. doi:10.3390/machines6020023

M. Mani, J. Larborn, B. Johansson, K.W. Lyons, and K.C. Morris. Standard Representations for Sustainability Characterization of Industrial Processes. *ASME. Journal of Manufacturing Science and Engineering.* October 2016; 138(10): 101008. 2016. doi:10.1115/1.4033922

D. Mourtzis, N. Papakostas, D. Mavrikios, S. Makris, and K. Alexopoulos. The role of simulation in digital manufacturing: Applications and outlook. *International Journal of Computer Integrated Manufacturing* 28: 3–24, 2018. doi:10.1080/0951192X.2013.800234

D. Mourtzis, J. Angelopoulos, and N. Panopoulos. Robust Engineering for the Design of Resilient Manufacturing Systems. *Applied Sciences.* 2021, 11, 3067. doi:10.3390/app11073067

M. Paju, J. Heilala, M. Hentula, A. Heikkilä, B. Johansson, S. Leong, and K. Lyons. Framework and indicators for a sustainable manufacturing mapping methodology. In *Proceedings of the 2010 Winter Simulation Conference*, pages 3411–3422, 2010. doi:10.1109/WSC.2010.5679031

H. Panetto, B. Iung, D. Ivanov, G. Weichhart and X. Wang. Challenges for the cyber-physical manufacturing enterprises of the future. *Annual Reviews in Control*, 47: 200-213, 2019. ISSN 1367-5788, doi:10.1016/j.arcontrol.2019.02.002.

SEMI Standard E35 - Guide to Calculate Cost of Ownership (COO) Metrics for Semiconductor Manufacturing Equipment. [available online at www.semi.org].

SEMI Standard E10 - Specification for Definition and Measurement of Equipment Reliability, Availability, and Maintainability (RAM) and Utilization [available online at www.semi.org].

SEMI Standard E79 - Specification for Definition and Measurement of Equipment Productivity [available online at www.semi.org].

J. Sääski, T. Salonen, J. Heilala and J. Mela, J. Economic evaluation of the use of augmented reality in assembly processes. In *Proceedings of Swedish Production Symposium, Stockholm 18-20 November 2008*. Lindberg B., and Stahre J. (eds.). The Swedish Production Academy, pages 409-416. 2008.

Visual Components https://www.visualcomponents.com/ [Accessed August 1 2021].

World Commission on Environment and Development (1987). Our Common Future. Oxford, Great Britain: *Oxford University Press*. 1987.