Material Flow Analysis

Hasse Nylund & Minna Lanz

Tampere University of Technology, Laboratory of Mechanical Engineering and Industrial Systems, Tampere, Finland

hasse.nylund@tut.fi, minna.lanz@tut.fi

Synonyms

Material Flow Study, Material Flow Investigation

Definition

Material flow analysis is the study of well-defined process chains where raw materials are transformed into goods and products that are consumed or used by end-users or customers.

Introduction

In this chapter, material in material flow is understood as goods or products that are consumed or used by customers. The focus in on industrial systems and flow of materials in industrial supply chains. The material flow is described with activities, the individual steps as well as a process that consists of several of the individual steps of activities.

Encyclopedia Britannica (2018) defines material as "*the elements, constituents, or substance of which something is composed or can be made*". Similarly, Rhee (2008) defines material to physical matter that is used to produce an object, which typically is some kind of product. Material can also be divided into substances and goods, where a substance is a single type of material, and goods can also be, in addition to substances, mixtures of substances (Brunner and Rechberger 2004). For example, metals belong to both of the categories. They are typically utilized as metallic alloys and in these cases they belong to the category of goods.

"Sustainable consumption and production aims at doing more and better with less." and *"It requires a systemic approach and cooperation among actors operating in the supply chain, from producer to final consumer*" are two issues of the goal 12, Ensure sustainable consumption and production patterns, from the 17 goals of United Nations to transform our world (UN 2018). The analysis of material flow plays an important role in these to understand and develop supply chains i.e. it serves a good starting point for improvements. The improvement issues are discussed from the viewpoint of value that is added in the process as well as key performance indicators to evaluate the improvement. Simulation is discussed as an efficient tool to study the material flow. Several aspects of simulation, related to material flow

analysis, are described. An example, a simplified case study is presented to emphasize the usefulness of simulation in the analysis and improvement of material flow.

Individual activities of material flow

The flow of material consists of several activities. Each activity can be described as input-process-output principle. These activities are connected together and form the wanted process i.e. the chain of activities. Moving from one activity to another activity requires a decision to find out the right activity.

The input-output principle

The simplest way to describe a process is presented in Figure 1. A process requires certain inputs, and produces outputs. The processes between can be categorized generally to transformation, storage, and transport of material (Brunner, and Rechberger 2004). These three categories can be used to describe the steps in any material flow on a general level. In transformation, the material becomes something different at the end state compared to what it was at the original state. Transport is the movement of the material to the next transformation process. Typically, when the material is transported, it ends to a some kind of storage, whether this is intended or not i.e., it will wait a certain amount of time before it can be transformed further.

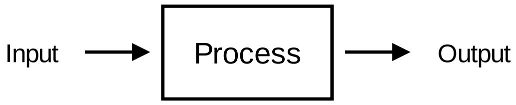


Figure 1. A basic presentation of a process with its inputs and outputs.

The process can also be understood as a system. A system is defined to have system boundaries. The input and output will cross the system boundaries i.e. the material flows into the system and out from the system. The process within the system can be viewed from several different levels. Enzler (2006) specifies these levels to company-internal processes, an entire company, supplier relationships along a supply chain, an entire supply chain, a region, and a nation.

The entire company can be seen as a factory and the company-internal processes from the viewpoint of material flow as workstations, cells, systems, and sections within a factory (ElMaraghy and Wiendahl 2009). A workstation represent a single step in the material flow in a factory that typically consists of one machine and an operator with the necessary tools. A cell consists of several workstations that include, in addition to the workstation, material handling inside the cell. A system in this context represents manufacturing or assembly system consisting of workstations and cells. It typically has some storages or buffers to store parts to be produced. The sections form the whole factory and typically include internal logistics between the manufacturing and assembly systems.

Material is not the only element that flows in processes. Hubka and Eder (1988), in their model of transformation system, categorize the inputs and outputs into material, energy and information. The transformation process itself consists of humans and technical equipment as an execution system as well as of information and management systems. Kurle (2018) also discussed the flows presented above and adds media and heat flows. Examples of media flows as inputs are lubricants, coolants, and water for processes and washing. These typically leave a system as outputs where their properties have changed. The changes are, for example, in temperature, quality, physical state, and pressure.

Material, as one of the elements of flow, can also be divided into different categories. Nylund et al. (2013) divide the inputs to virgin and recycled material, maintenance and repair as well as remanufacturing. The virgin and recycled material are typically bulk material while the maintenance, repair, and remanufacturing concern something, that has been processed earlier, used by customers, and returned to the system via reverse logistics. The division of the material elements can also be illustrated using sankey diagrams.

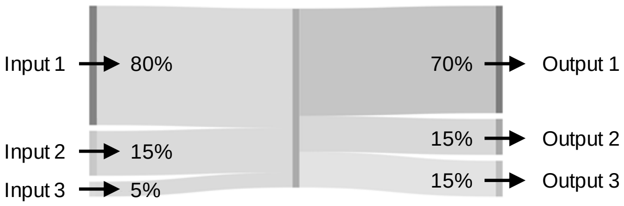
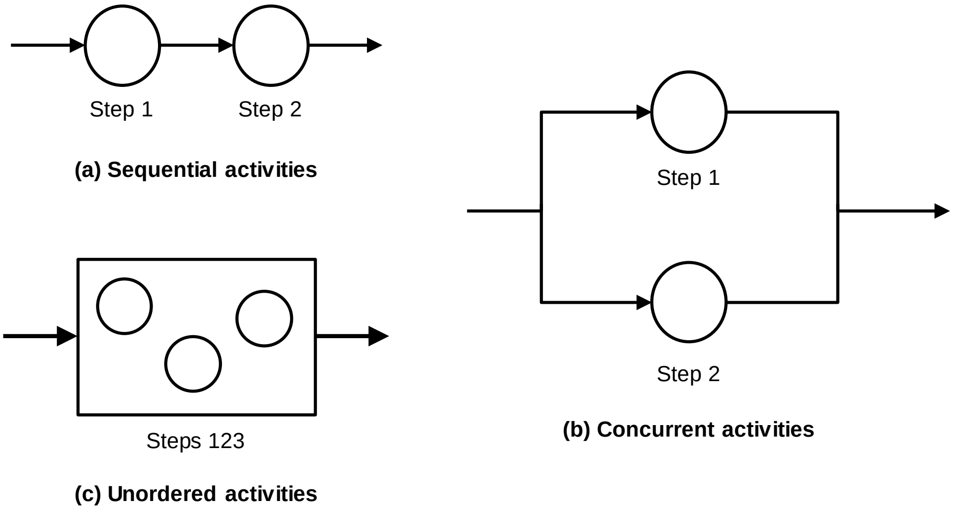


Figure 2. An example of a sankey diagram.

A sankey diagram can be used to classify different inputs and outputs with the amounts or portions of the total amount. In Figure 2, three inputs and outputs are presented with their portions with percentages. The three inputs could present different types of material used in a process while the outputs could be classified as e.g. products, materials that are recycled, and waste material that is disposed.

Types of individual material flow activities

The individual material flow activities can be classified into sequential, concurrent, unordered, and conditional activities (van de Weerd and Brinkkemper, 2008). Figure 3 shows the basic principle of them.



(a) Sequential activities

(b) Concurrent activities

(c) Unordered activities

Figure 3. Sequential, concurrent, and unordered activities.

Sequential (or serial) activities occur in a certain order. It is case dependent, if the next activity can start before the previous activity has ended. For example in machining, a part is typically manufactured using several different machines and the next activity cannot be started before the previous has ended, because the part has to be transported between the manufacturing activities. Painting is an example, where the activities can overlap. On a big surface, priming painting can take a long time and finishing painting can start when the priming painting is still going on. In the example of painting, the activities can overlap, but they will be finished in the same order they had started.

Parallel activities occur independently from each other. They may have a common previous activity e.g. a material shipment to a factory. After the shipment, the different activities can happen at the same time. In some cases, the different activities require same manufacturing resources. For example, an acceptance inspection may be required to receive parts. Even if they will advance parallel in different activities, they may be inspected using same tools and personnel and therefore form a queue of parts waiting for the inspection.

Unordered activities have no particular order they must be completed. These activities can occur in the order they can be started. For example, three separate sub-assemblies that are required in the same final assembly are assembled independently from each other. The order the sub-assemblies will be finished does not have an effect on the final assembly.

For more timely operations, a certain commonly agreed order of activities has several benefits, even when the activities do not require a certain order. The sub-assemblies of the previous example can be scheduled to be started at certain times aiming to have them ready for the final assembly at the right time. Similarly, if a sub-assembly is a complex process and takes time more than one shift, the assembly worker will change during the assembly. In this case, a commonly agreed assembly order helps to identify, what has already been done and what is still required to be done. This can decrease faults and rework of the assembly process.

The sequential, parallel, and unordered activities are the basic building blocks of many kind of flow of material. Typical system is a hybrid of these building blocks i.e. all of these basic blocks do exist in the material flow systems.

In order to control the material flow, conditional activities are needed. These are used to decide, which activity is selected, or when an activity can occur. There is generally two types of conditional activities i.e. diverging and converging activities (Kurle 2018). The conditional activities are presented in Figure 4.

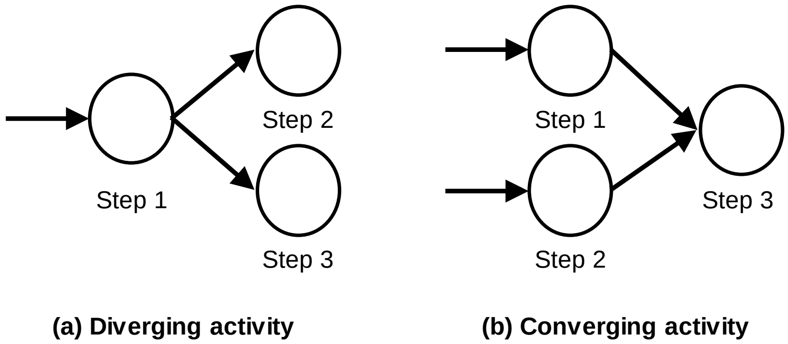


Figure 4. Diverging and converging activities.

In a diverging activity, there exists more than one alternative activity as the next possible activity. Therefore, there must exist a rule to select the next activity. For example, parts are normally manufactured using a certain manufacturing resource. When the resource is operating at its full capacity, the remaining parts are routed to a secondary machine, on a different activity. Another example is when similar products are manufactured and they are delivered to different customers.

The converging activity is opposite to the dividing activity, where parts from more than one different activities are required in the following activity. This is typical in uniting activities, such as in an assembly of two or more parts. The converging activity can occur only when the all the required parts are available for the activity.

Process chains of material flow

There exists several ways to describe the process chains of material flows. The individual steps in a material flow chain can be described with the activities discussed before. The process chain reveals a bigger picture and usually describes a larger system consisting of several different activities. The following techniques are common in describing material flow and are discussed in brief:

- Flowcharts
- Swim lane diagrams
- Precedence diagrams
- Sankey diagrams

It has to be noted that there exists several other diagrams to describe material flow. In addition, the presented techniques have different variations in their e.g. symbols and visual appearances. The most suitable technique is case-dependent and should always be carefully investigated. At many times, using a technique that is common within the organisation, is a good way to proceed. The persons involved get a better understanding if a familiar way to present material flow is utilized.

Flowcharts

The most common elements of flowcharts are terminators, activities, decisions, documents, and arrows to connect the other elements (ISO 1985). The terminators represent starting points and ending points of a system i.e. they are the boundaries of the system. A rectangular box present the activities of transformation, storage, and transport. When the activity is finished, a decision is made of what will happen next. The decisions are denoted with shapes of diamonds. Arrows are used to present the direction of flow between the activities. Parallelogram present input information required in an activity or output information from an activity i.e. the documents used or created in the process. Flowcharts can have other shapes to describe different issues and different implementations are applied for specific purposes.

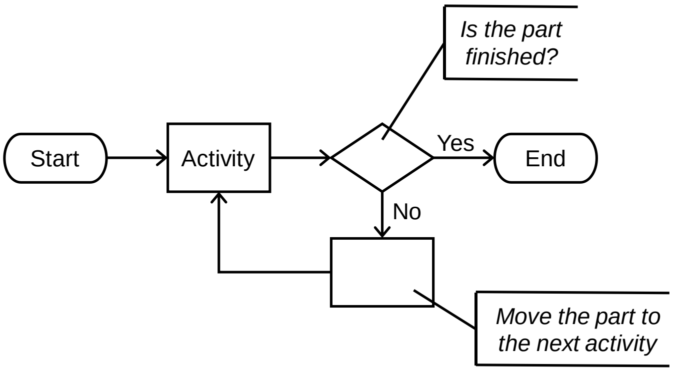


Figure 5. An example of a flowchart.

Figure 5 presents a simple example of a flowchart. It describes a chain of activities that are needed to manufacture a part. If there is still activities left, the part is moved to the next activity. After the last activity, the process will end. Note that the texts *"Is the part finished?*" and "*Move the part to next activity*" are usually inside the shapes. As the texts would not fit into the shapes, comments are used and connected to the symbols they are related to.

Swim lane diagrams

Swim lane diagrams can have the same or similar information that are presented with flowcharts. The main difference is that swim lane diagrams differentiate responsibilities for the activities with lanes (Rummler and Brache 1990). The process of the activities then changes between the lanes when the next activity requires actions from some other party. The responsibilities can be individual persons, such as a quality engineer or a group of persons e.g. assembly workers. The responsible party can also be a function of a company such as sales department or gear manufacturing shop. Figure 6 presents a general example of a swim lane diagram. The example uses the same symbols as in the flowchart example earlier i.e. rectangular boxes and arrows. Parallelograms present the input and output of information required and gathered from the activities. In some swim lane diagrams, different to the example in Figure 6, information objects are presented as documents in a separate lane in addition to the lanes for different responsible parties.

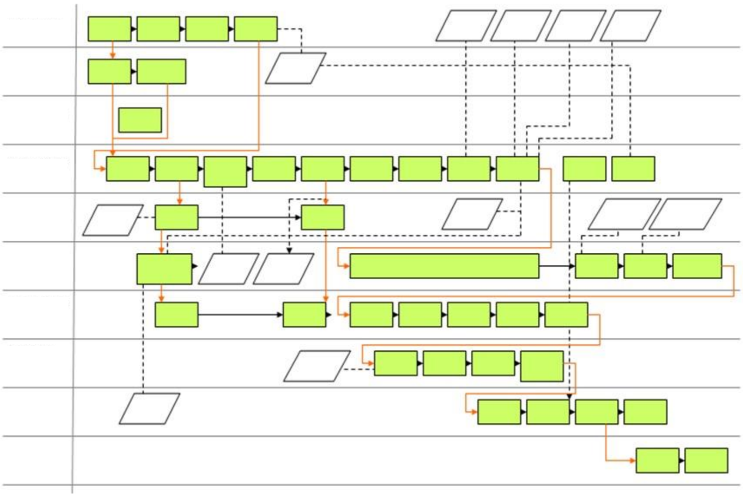


Figure 6. A swim lane diagram with different responsibilities in different lanes.

Precedence diagrams

A precedence diagram typically includes the activities and their dependencies. In Figure 7 there are activities from A to F. The diagram shows that the activity D is dependent on the activities B and C i.e. they must be both completed before activity D can occur. The activity E is also dependent of the activity C and therefore, it there is a problem at the activity C, only activities A and B can be completed.

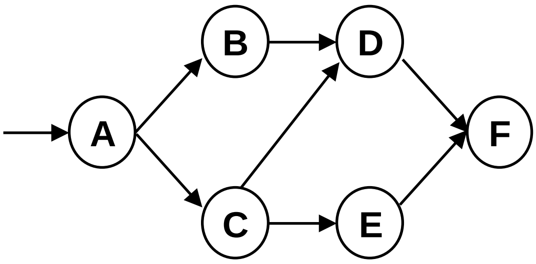


Figure 7. An example of precedence diagram.

A precedence diagram can have additional information e.g. the duration of the activity. For example, if the activity B takes 15 minutes and the activity C has a duration of 30 minutes, there exists 15 minutes time period between the earliest and latest starting time for the activity B. This can be utilized in planning and scheduling of the whole process.

Spaghetti diagrams

The spaghetti diagram illustrates a network of activities and the material flow between the activities, see Figure 8. The thickness of the lines indicates the amount of material transported between the activities.

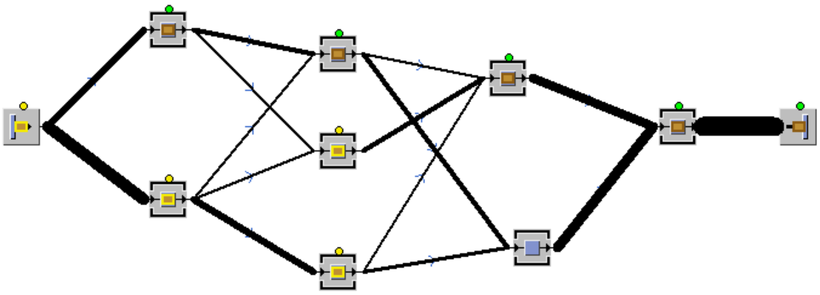


Figure 8. Spaghetti diagram showing the flow between different activities.

The diagram can also be formed into an actual layout of a system to find out where material flows within a facility. This can be used in planning the layout of a facility to improve the material flow. Manufacturing steps can be set close to each other based on the flow of material to minimize the movement of material. The spaghetti diagram can also be utilized to analyse the flow of people. This can be used, in addition to the setting the manufacturing steps close to each other, to plan short and safe pathways the people are using.

Product lifecycle view of material flow

The individual activities and the process several activities will form are principles to describe the flow of material. To a more concrete description, a view of product life cycle can be used. Jayal et al. (2010) divide the product life cycle to the stages of pre-manufacturing, manufacturing, use, and post-use. Similarly, the phases can be roughly divided into beginning of life, middle of life, and end of life (Rolstadås et al. 2012). Umeda et al. (2000) discuss five typical life cycles of products; traditional, recycling, reuse, maintenance, and post mass production paradigm (PMPP) as their proposed new manufacturing paradigm. Kumar and Putnam (2008) describe the traditional supply chain as cradle-to-grave resource management where the supply chain considering the reverse logistics is called cradle-to-cradle. These viewpoints share similar phases of product life cycle with different terminology and emphasis of the lifecycle. Figure 9 shows an example of life cycle of products that combines the viewpoints discussed above.

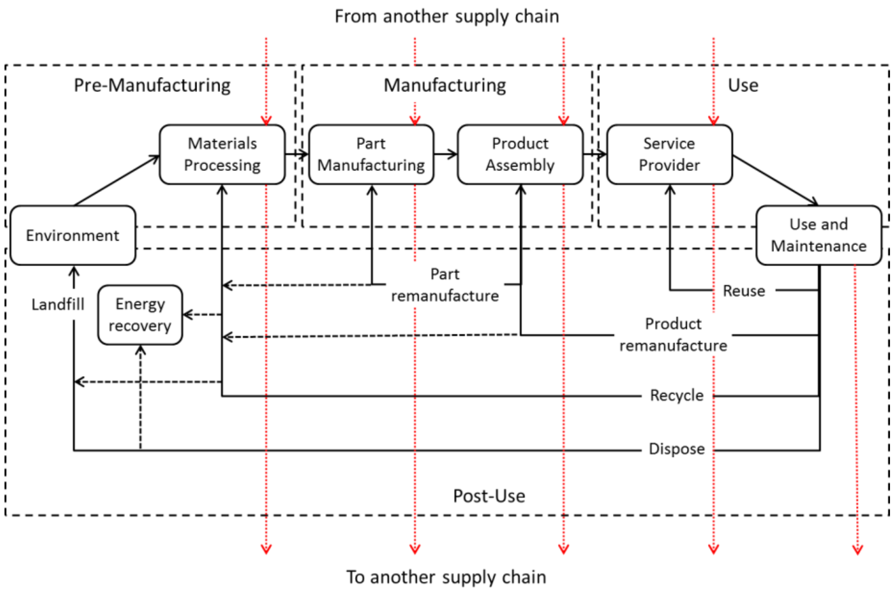


Figure 9. An overview of product lifecycle with reverse logistics.

For new products, the pre-manufacturing includes the extraction of materials from the environment, materials processing, and materials manufacturing. The materials manufacturing serves the phase of manufacturing offering blanks material. The manufacturing can be divided into part manufacturing and product assembly. The part manufacturing is typically making of individual parts and components that are joined together in the product assembly. The assembled product is a final product. The service provider represents the players between a manufacturing company and a customer. When a product is at a customer, it is used as well as maintained and repaired. In a linear economy consisting from the phases of pre-manufacturing, manufacturing, and use, the product is disposed after it is not used anymore.

The phase of post-use represents the reverse logistics in a product life cycle. In the reuse, the product is typically returned to the service provider or to the company that manufactured the product. If possible, the product is repaired and sold e.g. as a second hand product. In the product remanufacture, the product is returned to the manufacturer. The product is disassembled and each part of the product is investigated. Useful parts are reused directly and the parts that can be repaired will undergo the part remanufacturing process. Parts that cannot be reused, will be replaced with new parts. If the product cannot be reused or remanufactured, the next option is recycling where the materials of the product are used as recycled materials. The recycling may also occur in the product and part manufacturing phases if the components cannot be used and will then be recycled. Material that cannot be utilized as recycled material can be used in energy recovery and as a last option, as a landfill.

The vertical arrows in Figure 9 illustrate a situation, where material can flow from and to another processes. Recently, the term circular economy has been used to describe closed-loop supply chains. The main idea is to keep materials, components, and products in use rather than recycling or disposing the material (MacArthur et al. 2015). Therefore, the lifecycle of a product or it’s material can be prolonged in another lifecycle in a same or different purposes. Remanufacturing belongs to the scope of circular economy, but has been applied before the term circular economy was used. For example, Bras (1997) explained the supply chain with reverse logistics. One difference is that the term *demanufacture* was used instead of remanufacture.

Improvement of material flow

The flow of material can be analysed to understand the current material flow process. This is not typically the main reason for the material flow analysis. Instead, it is typically related to improvement i.e. what can be done to make the material flow better. In this, current state analysis and future state analysis can be utilized (Rother and Shook 1999).

One way to describe a process chain is to focus on the value that builds over time. Liker (2004) classifies the activities of a process chain as value-added, non-value-added but necessary, and non-value-added waste. It is important to define the value from a customer point of view in that the value-added activity is something from what a customer is willing to pay. These include typically the transformation activities of material, such as drilling a hole. Non-value-added, but necessary activities include e.g. transportation of material to a station, where the transformation occurs. This activity cannot be removed, but the distance may be shortened. An example of non-value-added waste is over production i.e. manufacturing higher quality than a customer requires. This takes more time and adds additional costs that a customer is not willing to pay. Additionally, a fourth type of activity can be recognized i.e. a value-destroying activity, which can happen e.g. because of poor management (Bowman and Ambrosini 2010). A failure in an activity may cause a part to be broken or may interrupt the process. This can lead to the rejection of the part, or additional rework requiring extra time and causing additional costs.

Identifying the activities that add value while the rest of the activities do not add value, helps to identify the areas of improvement. This serves to identify what could be done to improve the situation towards the future state. The focus on value-added activities discussed above mainly concerns economic and technological aspects. In addition to these, environmental objectives should be set. Examples of these are (OECD 2011; GRI 2015):

- Reduction of energy consumption and energy requirements of products and services
- Reduction of greenhouse gases and other significant air emissions
- Reduction of emissions into water
- Reduction of material usage and generated wastes
- Increased use of recycled materials and renewable energy

To understand the current state and to compare it with a possible future state, the states need to be compared using concrete metrics that indicate the differences between the states. Several typical performance indicators related to material flow are listed in Table 1 (OECD 2011; GRI 2015; Lanz et al. 2014):

Table 1. Material flow related key performance indicators

Focus of the measurement	Example key performance indicators
Economic	• Machine, material, energy, and employee costs per products, production line, and factory

	• Inventory level, value, turnover, time, and cost per type (raw materials, work in process and finished goods)
Technical	• Order-to-delivery and production lead times • Throughput rate i.e. amount of jobs done in a certain time unit • Resource utilization rate • Quantity and ratio of good, rework able, and scrap quality products • Quantity and ratio of products that are scrap and can be reworked • Delivery reliability
Environmental	• Material, energy, and water consumption • Use of recycled material and renewable energy • Greenhouse gas and other significant air emissions • Total weight of waste by type and disposal method • Environmental impacts of transporting products and other goods

Simulation as a tool in the analysis of material flow

"*A simulation is the imitation of the operation of a real-world process or system over time*" (Banks et al. 2010). In this chapter, discrete-event simulation (DES) is discussed in the context of material flow analysis. DES has been utilized in several different application areas. Based on Banks et al. (2010), DES has been utilized e.g. in the areas of manufacturing systems, construction engineering, military applications, logistics and supply chain, transportation, business processes, and health care. Examples of utilizing DES in the areas of manufacturing systems and supply chains in material flow related issues are (Banks et al. 2010; Bandyopadhyay and Bhattacharya 2014):

- In manufacturing systems, the simulation study typically focuses on material flow within a facility. The focus can be on the whole process of a factory from order to delivery. It can also be focused on a sub-system within a factory, or limited to certain products from the product portfolio.
- Simulation of supply chains focuses on bigger systems and the actual studied system may be a chain of different facilities existing globally in different areas of the world. When the system is bigger than a single facility, the level of details in the simulation is usually lower i.e. the level of complexity of the investigated system does not have to be higher. Biggest difference compared to a simulation of a single facility is the transportation activities between the facilities.

According to Carson (2005), DES is useful in several different situations. In analysing existing systems, if the system has some level of complexity and simple analytic model is not sufficient, simulation could be applied. At the same time the system cannot be chaotic i.e. the behaviour of the system can be defined. When new a system is designed, or larger changes are planned to an existing system, simulation can help to find out feasible solutions before any physical implementation. Simulation models, especially visual models, can help to get a common understanding and helps in training of employees to e.g. explain a new operation rule. Examples of material flow related issues that can be addressed by simulation are (Law 2015 and Robinson 2004):

- *Need for equipment and personnel*: What kind of machines and devices are required to achieve a desired flow of material as well as number of personnel to operate the manufacturing equipment.
- *Changes in customer behaviour*: Evaluating the effect of changes in product volumes and mix as well as the influence of introduction of new products and withdrawal of old products.
- *Operational procedures*: Policies of production planning, control, and scheduling to achieve timely manner of material flow.

The power of DES is in the experiments and analyzing several different scenarios. It allows the comparison of alternative designs and ways to operate a system (Carson 2005). The process is iterative i.e. many scenarios can be examined and only the feasible solution alternatives can be selected to be investigated further in mode details.

Elements of modelling and simulation of material flow

In DES the process types of transformation, storage, and transport discussed earlier, can be categorized into activities and delays (Banks 2003). The transformation and transport are activities and the duration of these process types are known prior to their execution. The duration of time an entity spends in a storage is a delay, and it varies between entities. The queue of the parts waiting for the next activity can be different between the arriving entities and therefore the time can also vary. Another example of a storage is when entities are produced into a storage and they are collected from the storage when the next customer order is realized i.e. the delay is dependent on when the customer order happens. The actual time of transformation and transport, from start to finish, may also be different from the duration that is already known. For example, a process can fail, and the duration until the failure is solved adds to the total time of the activity. It can also end to a situation, where the process will be ended and cannot be continued later.

Many commercial simulation software packages of DES have predefined and built-in objects for modelling the flow of material. The software packages use different terminology, but have similar functionality. The main difference is on how ready to use the objects are i.e. how much needs to be modelled for the specific case. As an example, the common objects related to material flow of one software package can be classified into (Bangsow 2016):

- Movable units of *entities*, *containers*, and *transporters*. The entities are typically the parts or products to be manufactured. Containers and transporters represent objects that are used to move one or more of the other entities. Other types of transporting objects are, for example, conveyors and pick-and-place robots.
- *Humans* act as the operators of the transforming activities and transporting the movable units.
- *Source* and *Drain* are objects that present the system boundaries. The source is the starting point of the system, where the entities of the system are created. The drain represents the opposite of the source. It removes to moving objects from the system i.e. it is the ending point of the system.
- *Single process* accepts only one entity at the time to the object. It is used to model a transformation activity of one individual entity.

- *Parallel process* behaves like the single process. The difference is that the parallel process accepts more than one entity. The entities are processed independently from each other. Therefore the parallel process can be used to model e.g. group of similar activities.
- *Assembly* requires one or more entities and it is used to process them simultaneously. This is a diverging i.e. joining or combining type of process, and the entity leaving the object is typically different than the ones that arrived into the process.
- *Dismantle station* acts opposite to the assembly, a converging process. One entity or one group of entities arrive at the object and different entities exit the object. In the case of group of entities, this is typically unloading or unpacking the entities and they may exit the object to different locations. In the case on one entity, the object may hold e.g. a cutting process, where the arriving entity is cut into two or more separate entities.
- *Buffer* represents an object of storage that is typically a step before a processing object i.e. it doesn't present a warehouse type of object. If an entity cannot enter the processing object, it will wait in the buffer until it can move forward. Buffers will have the entities in them in a certain order. This order can be manipulated and the most common orders are first in, first out, and last in, last out. Typically, the software packages offer other options to sort the entities in a buffer.
- *Store* presents a warehousing object, where entities are stored intentionally. When an entity enters a store object, it will remain in it until something requests in from the store.
- *Connectors* are used to connect the transforming and storing elements to define the flow of material. There exists also other ways to implement the selection of the next element.

The objects presented above are an example of common objects that represent the possibility to model a material flow system. Entities represent the products that are manufactured, and they are transformed, stored, and transported using the other objects. Common property for the transforming type of objects is a duration i.e. the amount of time the process takes. Also the rules for starting and ending of the process can be set. For example, a process is finished, but it will not advance until a worker unloads the entities from the process.

An example of simulation in the material flow within a manufacturing facility

In the following, an example of utilizing DES in material flow analysis is presented. The example has been used in education of university level students. It is a simplified example of a real situation. The reason for this is that the exercise is intended to be complemented within two hour exercise session. In addition to the performing the exercise, the students will write a report of the exercise reflecting of what they have learned.

The example is a simulation model representing a part manufacturing facility. The manufacturing process consists of material flow between the manufacturing steps of sawing, turning, and drilling, see Figure 10. The facility has three sawing and turning stations as well as two drilling stations. Six different parts represent the material flowing through the system. Typical manufacturing facility produces a greater number of different parts and the six parts are so-called type presentatives that present the part portfolio on a sufficient level (Schenk et al. 2010). These type presentatives do not necessarily match any individual part. More commonly, they are example parts representing an average attributes of a larger group of similar products. The main benefit using the type presentatives is to simplify the amount of data to be handled in the execution of the simulation runs. The average attributed are not necessarily constant values. They can have variation that can be defined with, for example, normal distribution having a defined mean time and standard deviation.

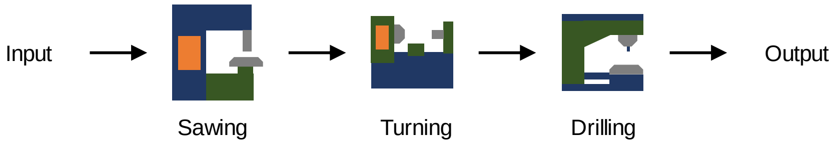


Figure 10. Basic presentation of the manufacturing process.

For the six parts, setup and machining times for the three manufacturing steps are given. Machining time presents the time of the value-adding activity i.e. the material removal. The setup time is a duration occurring between one part is finished and the machining of the next part is started. The setup times are given in a matrix, where the change from one of the six parts to any other takes different amount of time. Between some parts the changeover time is relatively small compared to other changeovers. The percentage of availability of the manufacturing steps is set to the individual machines. This means how much of the planned working time the machines can actually be used. This varies between the machines from 80% to 98%.

The objective of the simulation example is to manufacture 1143 parts in 10 days. The input rate of new parts to be manufactured is set in advance, and this cannot be changed in the simulation example. The number of manufactured parts, 1143, is therefore the theoretical maximum and when the value is reached, the objective of the simulation example is achieved.

In the initial scenario the three processing steps of the parts can be manufactured in any of the corresponding machines. The machines are selected in cyclic order i.e. the parts are evenly distributed between the machines. In this scenario, the objective of the number of parts cannot be achieved and therefore in the second scenario, the routing principles of the parts are changed until the objective is reached. This is typically done by trial and error, where the results of a simulation experiment are investigated and further changes are applied.

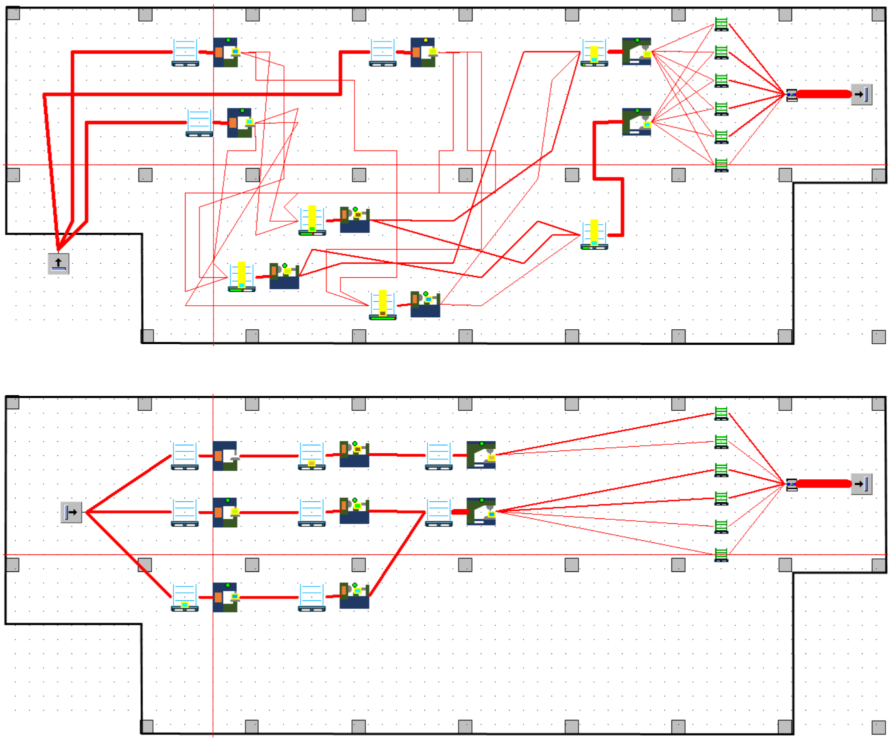


Figure 11. Spaghetti diagrams of the two scenarios.

Figure 11 shows the flow of material in the form of spaghetti diagram in the initial scenario as well as in the scenario, where the objective is reached. The material flow in the latter scenario, where the objective is reached, is significantly clearer. In addition to the main objective, the layout of the manufacturing facility is changed to eliminate unnecessary movement on the factory floor. The feasible solution was reached with the following changes:

- The setup times of the manufacturing steps were investigated and parts were grouped to the machines where the setup time between the parts were the lowest.
- The machining times were calculated and compared with the availability of the individual machines. Parts with the longest machining times were associated with the machines with highest availabilities.
- From the above, three groups of parts were formed. As the drilling had only two stations, the parts had to be divided differently between the drilling stations. This again was done by comparing the drilling times of the parts and the availability of the drilling stations.
- The layout was adjusted to better match the material flow and to avoid crossing flow of material.

The difference of the flow of material between the two scenarios is significant. Several numerical values were also gathered from the simulation scenarios. Main numerical results are presented in Table 2.

Table 2. Numerical results from the simulation example.

Numerical result	**Initial scenario**	**Objective reached**
Number of products manufactured	908	1143
Portion of setup times	23%	2,6%
Portion of machining times	77%	97,4%

Average throughput times of the parts	27 hours 40 minutes	1 hour 52 minutes
Average work in progress	135	9

The number of manufactured products increased 26 percent between the two scenarios. The main reason for this was the portion of setup times, which decreased almost 90 %. This results in that the saved time of reduced setup time increased the time for machining. As the input rate was set in advance, in the initial scenario the capacity of the machines was not enough. This can be seen from the average throughput times. The huge difference in these can be explained with the waiting times the parts spend between the manufacturing steps. The same can also be explained with the average work in progress, which increases as the capacity of the system is reached and parts need to wait longer in the queues.

Several issues discussed earlier in this chapter can be recognized from the simulation example. These include at least the following:

- Both sequential and parallel activities exists in the flow of material within the facility. These are controlled with the conditional activities having rules, how the parts are routed between the manufacturing steps.
- The flow consists of activities and delays, where the delays between the transformation activities are the main reason for the differences in the average throughput times
- The material flow in this kind of simulation example typically follows the principles on precedence diagram.
- Value-added time was increased in the second scenario. The setup is a non-value-added activity that is necessary to manufacture different parts. Therefore it cannot be removed from the process, but the time of setups can be minimized.

As many different discrete-event simulation software have a vast amount of possibilities, several different features could be implemented into the simulation example. The input rate of new parts into the system was fixed in the simulation example. Increasing the number of parts into the system could be used to investigate the maximum capacity of the system within the new rules for routing.

The results of the simulation example are related to the technical key performance indicators. With these results, when the consumed time of the resources and produced parts of the facility are known, several environmental and economic performance indicators can be calculated. If the cost of a machine time is known, the total cost can be calculated from the time the machine was used. Similarly, when the energy use of a machine in a certain period has been calculated, the total energy use during the simulation can be gathered.

Discussion

By knowing how a system behaves, gives a better understanding in how develop and improve the current state towards any short- or long-term objectives, the future state. In a bigger picture, analysing the material flow can support the objective *doing more and better with less* as stated in the Goal 12, ensure sustainable consumption and production patterns, of the goals to transform our world by United nations (UN 2018).

Understanding the individual activities of a material flow and the process they form, helps to describe flow of materials and to identify the areas of improvement. By focusing on the value the process adds, the areas of improvement can be recognized. With the right performance indicators, the correct improvement steps can be made.

The simulation example, even when it was a simplified, gave several different results to analyse the material flow. In the case, a low-cost solution changing the rules of material flow, gave a great difference to the results that did show improvements based on the changed flow of material. The same simulation technique can be utilized in the different phases of a product lifecycle to gain similar benefits.

Cross References

- Circular economy
- Lean manufacturing
- Green value chain
- Supply chain management
- Cradle to Cradle

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