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VASCO - Digging the Dead Man's Chest of Value Streams

René Berndt, Nelson Silva, Christian Caldera, Ulrich Krispel, Eva Eggeling
Fraunhofer Austria Research GmbH
Visual Computing
Email: {rene.berndt, nelson.silva, christian.caldera ulrich.krispel, eva.eggeling}@fraunhofer.at

Alexander Sunk, Gerhard Reisinger, Wilfried Sihn
Fraunhofer Austria Research GmbH
Production and Logistics Management
Email: {alexander.sunk, gerhard.reisinger, wilfried.sihn}@fraunhofer.at

Dieter W. Fellner
Institute of Computer Graphics and Knowledge Visualization (CGV), TU Graz, Austria
GRIS, TU Darmstadt & Fraunhofer IGD, Darmstadt, Germany
Email: d.fellner@igd.fraunhofer.de

***Abstract*—*Value stream mapping* is a lean management method for analyzing and optimizing a series of events for production or services. Even today the first step in value stream analysis – the acquisition of the *current state map* – is still created using pen & paper by physically visiting the production line. We capture a digital representation of how manufacturing processes look like in reality. The manufacturing processes can be represented and efficiently analyzed for future production planning as a *future state map* by using a meta description together with a dependency graph. With VASCO we present a tool, which contributes to all parts of value stream analysis - from data acquisition, over analyzing, planning, comparison up to simulation of alternative *future state maps*. We call this a holistic approach for *Value stream mapping* including detailed analysis of lead time, productivity, space, distance, material disposal, energy and carbon dioxide equivalents – depending in a change of calculated direct product costs.**

Keywords*–*Value stream mapping; lean management; content authoring.

I. Introduction

Value Stream Mapping (VSM) is an abstract lean manufacturing technique for optimizing the material and information flows from production up to the delivery of products to the customers. Usually this is done by drawing current and future state maps by hand, allowing the optimization of production by identifying bottlenecks and wastes. With VASCO [1] we introduce a tool, which supports the complete work flow from acquisition, to analysis of the current state, up to planning the future state.

Figure 1 shows a typical hand-drawn board template for data acquisition at the "shop-floor". The concepts of VSM are usually represented by a set of standard symbols, which got various properties attached. Typical properties, e.g., for a VSM process (which represents a production step like welding or assembly) include information about the process time, scrap rate, workers involved in the production, but can also contain data about published enhancements of traditional VSM, e.g., space usage for production and logistics, transport distance and transport time [2].

The history of designing process maps and flowcharts to represent the flows of materials and information in a factory can be traced at least back to 1915, where in a book by Charles

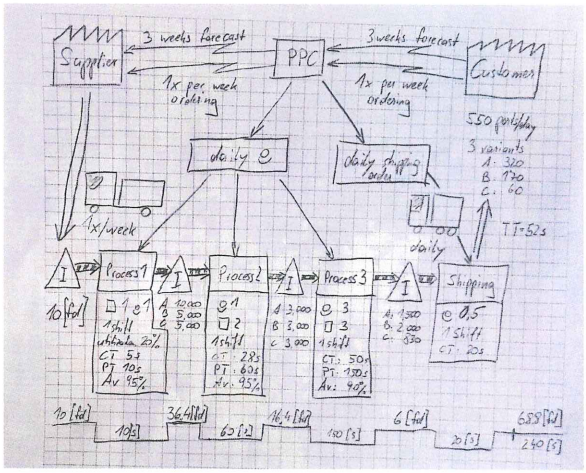


Figure 1. Typical hand-drawn VSM diagram created during a shop floor acquisition in a production facility.

E. Knoeppel entitled "Installing Efficiency Methods" we can find interesting graphical representations about the processes and routing in a manufacturing plant [3].

Nowadays, value stream mapping with traditional pen & paper method faces new challenges in practical utilization. Relevant problems or limitations for the approach presented here are: (1) indicators that are not aligned with a lean approach; (2) Processes measurements – problems/difficulties in measuring data in processes – cases where time data and quantity measurements are impractical due to layout problems, product complexity, or process type; (3) obsolescence of the current state map. The authors mentioned, that these problems and limitations can be addressed by use of ICT in data collection in production and using standards in measurement procedures. Thus, reproducibility and repeatability evaluation of CSM and alternative FSMs will be possible in the sense of supporting management in decision making. Furthermore, it is mentioned that VSM supports management when improving production conditions regarding Eco-design by identifying and eliminating environmental wastes [4].

Hence, it is necessary to have company wide standards for drawing, data collection and analyzing current state maps. Therefore, VASCO was established to close this gap for standardized analysis of CSM as well as enabling the planning of successful FSMs of value streams in a digital manner. As a result, a better decision making on shop floor level is supported when applying VASCO continuously.

The next section will give an overview of the related work and programs which inspired the creation of VASCO. Section 3 shows the main functionality of VASCO, how VSM diagrams are modeled within the system and how the automatic calculations are handled. Following, section 4 describes the underlying model based approach to calculate VSM-KPIs by entering resource consumption as input parameters. In section 5, a use case is presented to show VASCO in action and trying to close the gap from a practical point of view. Section 6 shows how VASCO can be used within dynamic simulation studies to enhance traditional "static simulation" of VSM. The last section concludes our work and will give an outlook on further research.

II. Related Work

VSM was originally developed as a method within the Toyota Production System [5][6] and introduced as a distinct methodology by Rother & Shook [7]. VSM is a simple, yet very effective, method to gain a holistic overview of the conditions of the value streams within a production environment. Based on the analysis of the current state maps, flow-oriented future state maps are planned and implemented [7], [8], [9].

A value stream includes all activities, i.e., value adding, non-value adding and supporting activities that are necessary to create a product (or to render a service) and to make it available to the customer. This includes the operational processes, the flow of material between the processes, all control and steering activities and also the flow of information [10]. In order to assess possible improvement potential, VSM considers, in particular, the entire process time (sum of time of all production steps) compared with the overall lead time (time from the customer ordering to the moment of delivery). The greater the distinction between operating time and lead time the higher the improvement potential [8].

Several organizations and researchers described sustainability indicators in their works but, however, there is no universal standard published yet. Further development of sustainability reporting in the production practice can be identified [11]. This made it important to define criteria that help to develop strategies for the evaluation and improvement of sustainability [12]. Paju et al. list a compilation of indicators, which can be used in a Sustainable Manufacturing Mapping [10]. In the following widely used indicators, like used, i.e., in the GRI standard [13], are explained. The following indicators are necessary to evaluate:

(a) **Disposal** due to waste of the resource 'material': Here, the legal EU definition of waste *'(...) means any substance or object which the holder discards or intends or is required to discard'* [14]. Material waste means all non-productive output (NPO) including solid and fluid waste [15]. An established categorization for produced waste is taken from the 'DIRECTIVE 2008/98/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL' [14], which orders the 'R' strategies reuse, recycle, recovery and disposal descending by importance. The reduction of waste therefore begins with prevention, followed by reuse or recycle and (thermal) recovery [16]. The efficiency of a manufacturing system is defined with the ratio of output in comparison with the input. Despeisse et al. explain that a system which utilizes the generated waste internally and sees it as a resource is more efficient than a system that does not so. Additional approaches such as redesign and re-manufacture [17] are not considered in this paper, since they are not applied in VSM.

(b) **Solvents**: Depending on the manufacturing process solvents are used in paints or adhesives. In the literature solvents are used as sustainability indicators [13].

(c) **Water**: often used for cooling, heating or cleaning in a production process [11]. E-VSM primarily focuses on water [18].

(d) **Energy and CDE/carbon footprint**: Since non-renewable energy has a direct impact on greenhouse gas, energy must be seen as an important indicator for sustainability [17]. Common energy and material forms in production which are used as sustainability indicators are electricity, natural gas and compressed air [10]. Furthere diesel or district heating can be included [19] more diesel or district heating can be included [19]. Several approaches exist in order to measure and improve energy and CDE indicators:

(i) Usually, the energy efficiency as quotient of net production value and primary energy consumption with the unit EUR/MWh, is used as a characteristic value and the system of the production is seen as a black box [11].

(ii) Modeling approaches in the traditional factory design with the objective of energy and resource efficiency [20]; [21].

(iii) The specification DIN EN ISO 50001 as amended, supports companies to establish an energy management system as well as during operation of the processes in order to achieve an improvement in energy efficiency, the use of energy and the energy consumption.

(iv) various approaches for CO2 assessment over the entire product life cycle, while the phase manufacturing (production) is usually represented as a single object in the entire modeling [22]. Analogous to accounting, the resource deployments are considered overall and calculated to the finished products [23].

(v) In the method carbon footprint analysis, the total greenhouse gas (GHG) emissions are estimated in terms of carbon equivalence (i.e. as tons of carbon dioxide equivalent [tCO2e] or grams of CO2 equivalent per kilowatt hour of generation [gCO2eq/kWh] from a specific product [24].

(vi) In Value Stream Mapping, different approaches are known to set the focus on environmental sustainability in order to obtain economic improvements as well. The method Energy Value Stream Mapping [8] with focus on energy saving examines each manufacturing step in energy intensity and energy waste, both in operating and start-up and shut-down phases. The work of Erlach is practical and supports direct implementation of energy savings by guidelines [25]. But only the resources and energy media Electricity, gas and compressed air are examined. An overall CO2 assessment is not supported.

(vii) 'Multi-Layer-Stream Mapping' (MSM) evaluates all processes in the value stream by efficiency-data, by comparing the value-adding to the total energy- and resource use. The aim is to get 100% efficiency at all stages of production. A

visual indication of the waste supports the user communicating the saving potential. This indication is not only applicable to resource inputs with environmental impact, but the CO2 assessment is not supported [19].

(viii) the approach to assess energy value-streams in production and logistics in respect of time- and energy-consumption (EVSM) focuses on aligning use of energy to value adding and non-value adding shares in operating times with scope of periphery 1-3 in a detailed way. The views of Hopf, Haag and Lourenco are combined in this approach [26].

(ix) SVSM is able to rate the waste-generation in value stream using a model which is integrated in VSM-Tool VASCO [27]. In summary, core ideas of the presented approaches are implemented in the model of VASCO. This allows management to identify possible improvement potentials and quantify them. Hence, a goal-oriented prioritization of measures to improve the value stream is supported.

Value stream simulation can be used in lean manufacturing to support the optimization of production [28]. It allows an early stage insight into productivity, effectiveness and service level without the need of creating detailed and time consuming simulation models. This means that a simulation in lean management workshops can now be done by lean experts instead of relying in simulation experts. Traditionally VSM is a pen & paper tool that captures the state of the system at the state it was drawn. Component based modeling divides the simulation into a set of simulation blocks [29]. These blocks can be used to create value stream maps that are generic and reusable. In our application VASCO, we also support several reusable blocks that allow the user to easily create value stream diagrams that are reusable in a standardized way. By utilizing standard simulation building blocks one can easily know the state of the system under different circumstances allowing for better decision making. Another important aspect of using value stream maps and specially in a digital form, is that the production and delivery processes are optimized from the customers' point of view [7].

In the seminal work of Wei Xia and Jiwen Sun [30] on simulation guided value stream and lean improvement, the authors give a good description of a typical value stream mapping application. This typical application is then enhanced by the usage of event simulation in the manufacturing process. The authors discuss how that greatly contributes to a better perception of the entire value stream mapping (VSM) and simulation processes. In the work of [31] a simulation model is used to evaluate the performance of an automotive manufacturing system as a function of demand. Prakash and Chen [32] developed a simulation model of a flexible manufacturing system, and investigated its performance. In the work of Welgama et al. [33] two cell designs were analyzed, for a manufacturing facility taking in consideration operator and material handling utilization factors. Kyukab et al.[34] used simulation to identify parameters to improve system performance at a motor production facility. Bischak [35] describes simulation in performance evaluation of a textile manufacturing module with moving workers. Park, Matson and Miller [36] describe a simulation approach used to verify that the daily throughput requirements can be met at a new assembly plant, and it is used to determine the maximum throughput of the facility, and to characterize how the component buffers behave in terms of quantity fluctuations and identified possible system bottlenecks. Shang et al. [37] uses a combination of simulation and optimization to evaluate the design of a cellular manufacturing system. In the work of Persson [38] the author investigates the impact of a varying level of system structure detail, when modeling a manufacturing system. Suri et al. [39] used simulation to validate analytic models and predict the system performance for a single material handling device case. In addition to using simulation to directly analyze and predict system performance, simulation has been used to validate analytic models [39]. There is not much work reported regarding manufacturing and simulation based methodology [40]. Additional and detailed examples of VSM simulation are needed in different types of actual production settings.

VSM is also seen as a tool to show the outcomes in a shorter period of time at minimal costs. The lean consultants can now represent and capture the current state of the process at a certain state and time and start projecting the future proposed state of the value stream. Based on lean concepts the two states can be simulated and key measurements are assessed. These simulation results can easily demonstrate the improvements [41]. In manufacturing, there are three types of operations that are undertaken to represent a type of waste that might occur: non-value adding, necessary but non-value adding and value-adding operations [42]. The first type is pure waste with unnecessary actions that should be completely eliminated. The second type involves actions that are necessary but might be wasteful. The third type are value-adding operations representing processes that convert raw materials into finished products.

The capture of information to a digital form is often not sufficient. From the point of view of using a digital tool to capture the state of a process, there are several applications that can be used and are available. However, in their paper, Shararah et al. [29] introduce the Value Stream Map Simulator using ExtendSim (VSMSx) as a powerful tool designed to facilitate the implementation of lean manufacturing by simulating the value stream map through standardized simulation building blocks. The company Siemens created as part of their Product Life-cycle Management - PLM product line, an optional extension library called Plant Simulation Value Stream Mapping (VSM) Library [43]. The company immediately reported productivity increases by as much as 20 percent and improvements of 60 percent related with the reduction of inventories and cycle time. Other benefits such as investment risk reduction (through early feasibility analysis capabilities), better line planning and allocation and significant increases in the resource utilization were also highlighted. The capability of being able to define what-if scenarios without disturbing existing production systems during the planning process is pointed as one of the most important features of any value stream mapping planning tool. Plant simulation is also referred as an important feature of such systems, because it facilitates the comprehension of complex production systems and processes. Resource utilization, material flows and supply chains maybe therefore optimized. The question of "Why perform value stream mapping in Plant Simulation?" is also debated in this technical report. Factors such as the reduction of cost for data collection by reducing the number of objects describing the processes (by utilizing pre-defined logic blocks) or the reduction in analysis effort through automated analysis modules have an important role in deciding to use

VSM. In order highlight the dynamic effects (which remain hidden in the static paper based mapping of the value chain), a digital representation (through computer simulation) of the value stream is required.

According to Nash & Poling [44], the value stream mapping has some disadvantages associated with it. It points to the fact that originally, VSM did not include any significant monetary measure for value. It is the stakeholders responsibility to determine determine which activity can be marked as value as well as which activity can be marked as waste. The task of decision-finding may take a lot of valuable time.

Another important challenge arises from the fact that there is the need to not only capture data and information about the processes and the information flows involved, but also it is beneficial to have a digital representation of how these processes look like in reality [45], in fact ultimately we would like to achieve what is sometimes called "The Digital Twin Concept Model" [46]. Similarly, in our approach we are taking the steps necessary to provide this type of vision. When we analyze the current arrangement of an assembly line and we capture this information on a VSM diagram (current state). At a later stage we do not want to come back to the production area to visual re-check the arrangement of machines, workers, to discover how are the parts actually delivered and stored or to know what are the space constrains to be able to describe and demonstrate how the actual work of the existent implemented processes is being performed. To have a better view of what should be improved when preparing the future state VSM, it is desirable that the new digital tool for the creation of VSMs can allow the users to capture and then to find annotations in the form of pictures, videos or 3D representations of the past, current and future reality of the production sites. Therefore, every time a user is handling a VSM diagram, he will be able at any step of the process to access these digital catalog of the different processes, that are now linked to the VSM digital representation.

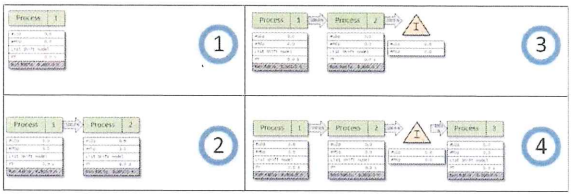
A field research on available standard software tools showed a lack in possibility of detailed analysis. While some tools just provide basic drawing aids for creating value stream maps (e.g. Microsoft Visio [47]), other tools like iGrafx [48], Plant Simulation [49] or SmartDraw [50] also support lead time calculations and basic simulation. None of them considers the availability of data in production lines, which is a big deal nowadays in order to cope with all the complexity and achieve transparency. Nevertheless, detailed analysis and transparency of value streams are needed to reveal improvement potentials.

To address the challenges in mastering the increasing complexity in the VSM data models, we are developing a highly customizable tool for authoring and managing value streams. The next section gives an insight on the key features of VASCO.

III. VASCO Main Functionalites

VASCO is implemented as a Microsoft Visio Plugin. This allows to reuse the drawing and connecting shapes functionality already provided by Visio. A VASCO value stream diagram can be combined with other shapes and features included by Visio or other 3rd-party AddIns. One important aspect in the design of the VASCO focuses on the user experience. Figure 2(a) shows the ribbon toolbar for VASCO. All available control elements are optimized for the fast creation of VSM diagrams,

(a) The VASCO ribbon which offers a support for fast generation of VSM diagrams.



(b) Drawing a simple VSM.

Figure 2. With minimum user interaction the drawing process in Figure 2(b) can be achieved with our VASCO toolbar shown in Figure 2(a)

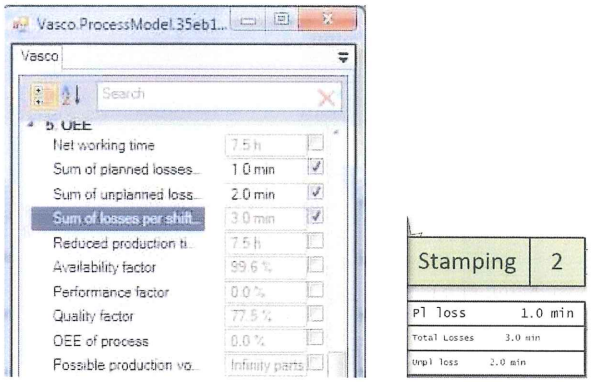
especially adding and positioning process or buffer symbol. Typical repeating tasks are automated like the adding of serial process/buffer symbols, where VASCO already connects the two symbols using an internal flow connector. The inserted process/buffer stays selected, so that the user can immediately use the commands "Add serial process"/"Add serial buffer" multiple times. Figure 2(b) shows how to create a VSM diagram. From (1) to (4) using only mouse clicks - or if you are on a touch device, then only 4 touch events are needed, which is much faster then a hand-made drawing. Therefore, the usual manual steps of transforming the hand-made drawings into digital documents is now completely obsolete when using VASCO.

A. Definition of VASCO symbols

As seen in figure 3 a value stream consists of a variety of standardized shapes and information. VASCO adds properties and the calculation logic to the VSM shapes to the main VSM symbols:

Figure 3. The standard VSM symbols (from left to right): Supplier, Customer, Process, Buffer, External flow, Internal flow.

- The **supplier** is the manufacturer which ships the goods into the factory.
- The **customer** is a company, merchant or another entity who orders goods and requires them to be shipped regularly. The customer determines the demand and the resulting takt time, which is a key value driving almost all calculations within a value stream.
- The **process** is a step, which adds value to goods by altering or modifying it.
- The **buffer** is an intermediate step where the factory goods are stored. This storage might be an input for the next process, a general depot for delivering goods to the customer or from the supplier.
- The **external flow** connects a supplier or a customer with a buffer or a process.



(a) The complete property model of the stamping process.

(b) Selected attributes of the property model displayed below the process symbol. 4(a).

Figure 4. The properties of the stamping process and how the process is displayed on the VASCO sheet.

- The **internal flow** connects buffers and processes with each other. The main difference between an external and an internal flow is that a internal flow might connect a process with multiple buffers or processes. This means that the internal flow is augmented with a property called material spreading which defines how many percent of material spreads from one process or buffer to their successors.

A valid *value stream graph* consists of one supplier at the start, one or more customers at the end, one or multiple processes, and zero or multiple buffers. Each of the processes and buffers are connected with internal flows and two external flows connecting the supplier and customer with the network.

B. Intelligent Symbols

One of the significant features of VASCO is that all symbols defined in Section III-A, are fully customizable by a configuration file. This configuration file defines which properties are added to the symbol. These properties can be classified into two major categories: manual input values or calculated values. The manual values are entered by the user, whereas the calculated values depend on a formula consisting of manually entered or other calculated values. The formula definition is also part of the configuration file and can be modified even at run-time.

For example, let's have a process which drills a hole into a plate. This process has two manual input values. The value adding time which is the time period when the drill actually drills the hole and the setup time. The setup time is the time period needed for positioning the drill and the time the assembly line needs to bring the plate into position. With these two values in the process it is possible to add a third value, the process time which automatically calculates the sum of the setup time and the value adding time. This automatic calculated value can be displayed on a databox in the process shape (see Figure 4). If a value of these properties changes, all dependent values are updated immediately (see Figure 4(a)).

One special case of calculated values is when the values not only depend on the local process, like in the example above, but also in other places from other symbols, like the following processes. These special calculations are called graph calculations. The graph calculations are also defined in the configuration file, but require a complete value stream graph in order to perform their calculations. For this, VASCO has two different modes. The first mode, is the design mode. In this mode the user can add processes, buffers and connect them with each other. The calculations which are only local are calculated in this mode. The second mode, is the calculation mode, where all graph calculations calculate their value. In this mode it is not possible to add, remove or connect symbols with each other.

To get a better picture about the calculation mode consider a customer who requires 100 items. We have 3 processes which are connected in series. Each process has a scrap rate of 10%. Now each of the processes has to accommodate the scrap rate of the following processes and produce more goods. That in the end the customer gets his 100 items. Therefore, in our example the first process requires 139 items. This example can become arbitrarily complex with parallel processes and the material spreading in internal flows. In the calculation mode all values are live updated and displayed. So if the customer requests that the factory delivers more items, it is then immediately visible how many more raw material the first process requires. This is also the reason why it is not allowed to edit the path, remove or add further processes during the calculation mode, as all values would be invalid with a unfinished value stream graph.

When a user adds a new intelligent symbol to a diagram, e.g., a buffer, this symbol becomes now automatically the current selected symbol. This allows the automation of the possible next choices for symbols that can be added to the diagram (connected to the current symbol). In this way, when the user looks to the application main toolbar, only symbols that are possible to be connected to the previous symbol, are available for a next drop in the diagram. When the user intent is to connect two symbols, e.g., the user wants to connect a buffer with a process, the user pre-selects these two symbols. After this step, the application automatically highlights the possible connections that can be added between the selected symbols. The users reported that these methods significantly improve the productivity and the usability of our application interface. These and other improvements will be the target of future studies, where we will access the overall usability of the tool and compare it with other existent VSM applications.

C. Key Performance Indicators (KPI) and Data Lines

As referred in the related work section, an important aspect in the analysis of VSM diagrams is the extraction and automatic calculation of *Key Performance Indicators* (KPI).

Key performance indicators can be calculated locally, e.g., for a single process (e.g. OEE rate) or buffer (e.g. local lead time) - but also for the value stream (e.g. total lead time) as a graph-based calculation. These values are calculated automatically and are visualized in several data lines below the drawn value stream.

When discussing with the main key holders (manufacturing and production consultants or VSM and processes simulation owners) involved in the event of capturing processes and information flows (as well as many other related information captured now in a digital form), one of the most desired features is the capability of calculating improved business metrics.

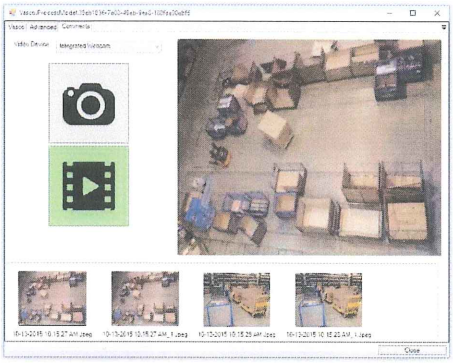


Figure 5. The Comments plugin allows to annotate VSM symbol with photos and videos taken from the camera of a tablet.

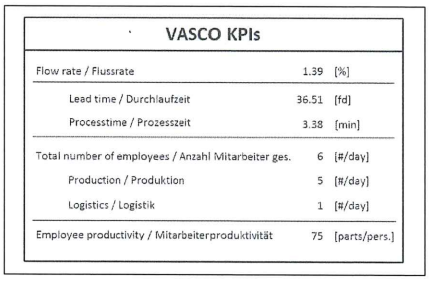
These metrics allow the evaluation of factors that are critical to the success of an organization. In our tool we calculate and present metrics that are related with human resources, costs, performance and workload balancing management. These are essential to the reduction of costs and to the improvement of performance of processes and persons.

We present results to the users in a concise way through resume maps in each step of the calculations procedures. This is a realistic and simple way to digitally represent the past, current and future reality inside all manufacturing sites.

D. Extensibility

One key-feature of VASCO is extensibility. While self being an Microsoft Visio addin, it can be customized by plugins itself. The basic version of VASCO is already shipped with three plugins, extending the basic functionality of the tool:

- **Comment-Plugin** VASCO was designed to make the acquisition and calculation of a new value stream easier and to replace the pen & paper acquisition. With the pen & paper method it is always possible to add different comments to the different symbols. In order to give the VASCO user a similar feature during the acquisition a comment plugin was created. This comment plugin enhances every symbols on a VASCO page with a comment tab (see Figure 5). When we observed during the data acquisition process that users sometimes only copied key figures from a machine into this comment tab, we further enhanced the comment-plugin with a snapshot ability. With this snapshot ability the user doesn't need to copy the values himself. The user only has to take a snapshot with the tablet. It is also possible to record a video with the comment plugin. This can be done to record different views of the machine or to record the voice of the person who does the acquisition so that there is not even the need to write textual facts in the comments box.
- **KPI-Plugin** The KPI-Plugin adds an additional visual features (see Figure 6) to the Visio page. This shape displays the key performance indicators of the factory in a clear fashion. Once a VASCO graph is complete and VASCO itself is in calculation mode, the values are calculated and automatically updated when a value in the graph changes.



VASCO KPIs		
Flow rate / Flussrate	1.39	[%]
Lead time / Durchlaufzeit	36.51	[fd]
Processtime / Prozesszeit	3.38	[min]
Total number of employees / Anzahl Mitarbeiter ges.	6	[#/day]
Production / Produktion	5	[#/day]
Logistics / Logistik	1	[#/day]
Employee productivity / Mitarbeiterproduktivität	75	[parts/pers.]

Figure 6. The Key Performance Indicator giving an overview of the operating numbers in the factory.

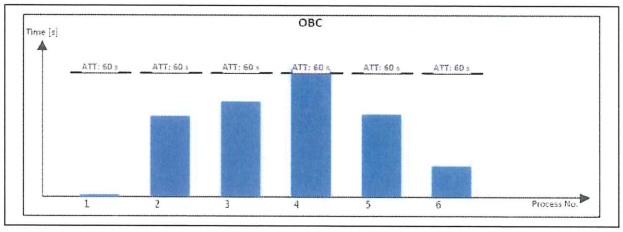


Figure 7. OBC showing the process time in relation to the takt time.

- **OBC-Plugin** The operator balance chart (OBC) visualizes the total amount of work of each process compared to the takt time. An OBC supports the critical task of redistributing work elements among operators. This is essential for minimizing the number of operators needed by making the amount of work for each operator very nearly equal to, but slightly less than, takt time [51]. Figure 7 shows the OBC chart of the given example.

IV. Model-based, Process-oriented Calculation of Resource Consumption

This section describes the 'ideal-typical re-utilization cycle'. It is the basis for evaluation of sustainability indicators in value streams. In each process of the value stream an ideal-typical re-utilization cycle is underlain virtually. Each ideal-typical re-utilization cycles includes the mentioned categories to handle waste: reuse, recycle, recovery and disposal. However, usually additional material is required in production which is not used for producing finished products. This creates waste of material resources. Waste of material resources is assigned to each ideal-typical re-utilization cycle of a process. Waste occurs depending on process technology. This waste can be reused, recycled, recovered or brought to the disposal site. But before immersing into the ideal-typical re-utilization cycle and the calculation of sustainability indicators, the connection of the elements of a value stream as process chains need to be discussed. A series of processes combined with parallel material flows lead to highly dependent elements (processes, buffers, transports) of the value stream.

A. Cumulated Scrap Rate

With a serial sequence of processes of a value stream and the occurring scrap rates at processes, each upstream process has to produce more to finally provide the required amount to the customer. Contrary to the direction of material flow the cumulated scrap rate increases for each process of the value

stream accordingly. As a result, the calculation of cumulated scrap rate for each process in a serial sequence is:

$$S_{cum}(i) = 1 - \prod_{i=n}^{1}(1 - s_i) \quad (1)$$

- s_{cum} – cumulated scrap rate along a value stream [%]
- s_i – scrap rate of a process i [%]

Starting from the actual customer demand D_{net}, the customer demand per process (i) results in:

$$D_{net.p}(i) = \frac{D_{net}}{1-s_{cum}(i)}$$

- $D_{net.p}(i)$ – increased net demand per process due to cumulated scrap rate at process i [parts per time period]
- D_{net} – net demand of customer [parts per time period]
- s_{cum} – cumulated scrap rate [%]

This formula is essential for the calculation of total waste along a value stream. Another effect of the cumulated scrap rate is not considered in this paper, but should be mentioned because of practical relevance in Value Stream Mapping: The cumulated scrap rate causes an increase of the required net demand per process upstream the considered value stream. Therefore, the customer tact time is not assumed to be constant for each process. Strictly speaking, the specific tact time of each process has to be reduced due to an increased required net demand while keeping available net working time constant.

B. Calculation of waste at single processes

The waste of material resources for each process in the value stream is, as described above, associated with the ideal-typical re-utilization cycle. This waste can generally occur in three ways; see Formulas 3, 4 and 5.

$$W_{nok} = (D_{net.p} - D_{net}) \cdot d_n$$

- W_{nok} – waste due to cumulated scrap rate [kg per time period]
- $D_{net.p}$ – increased net demand of customer [parts per time period]
- D_{net} – net demand of customer [parts per time period]
- d_n – net weight of input resource [kg per part]

W_{nok} is the waste because of not fulfilling quality requirements such as damaged or improperly manufactured parts. The gross material input is d_g. Due to the chosen manufacturing process additional resource input W_{ok} is often necessary and calculated as follows:

$$W_{ok} = D_{net.p} \cdot (d_g - d_n)$$

- W_{ok} – waste due to material input difference [kg per time period]
- $D_{net.p}$ – increased net demand of customer [parts per time period]
- d_g – gross weight of input resource [kg per part]
- d_n – net weight of input resource [kg per part]

The net material input is d_n, e.g., the material input differences between gross and net is sprue in injection moulding or paint sludge in the painting processes. As a third category, waste because of set-ups $W_b(i)$ is introduced. This waste is usually produced in batch production or discontinuous shift models. The above proportions of all waste depend on the considered time period. The waste proportion because of set-up is usually not in the same observation period as the required amount of the customer D_{net}. For this reason, the following proportionality is presented:

$$\frac{W_r(i)}{D_{net.p}(i)} \propto \frac{W_b(i)}{b(i)}$$

- W_r – waste due to set-ups [kg per time period]
- $D_{net.p}$ – increased net demand per process due to cumulated scrap rate [parts per time period]
- W_b – waste per batch [kg per batch]
- b – batch size [parts per batch]

W_b presents the average waste per batch; b is referred to as batch size. The sum of waste per observation period, e.g., shift, is calculated as follows:

$$W = W_{nok} + W_{ok} + W_{set-up}$$

- W – total waste [kg per time period]
- W_{nok} – waste due to cumulated scrap rate [kg per time period]
- W_{ok} – waste due to material input difference [kg per time period]
- W_{set-up} – waste due to set-ups [kg per time period]

To convert the waste per unit the calculated waste per observation period must be divided by the observation period. Thus, the waste per part w(i) for each process i is:

$$w(i) = \frac{d_g(i)}{1-s_{cum}(i)} - d_n(i) + \frac{W_b(i)}{b(i)}$$

- $w(i)$ – total waste per ok part [kg per ok part]
- d_g – gross weight of input resource [kg per part]
- s_{cum} – cumulated scrap rate [%]
- d_n – net weight of input resource [kg per part]
- W_b – waste per batch [kg per batch]
- b – batch size [parts per batch]

The waste per unit can be calculated for each process and each resource which is used. This waste of material resources is supplied to the ideal-typical utilization process and rated. Simplifying the mathematical model, only the primary resource is considered, which excludes process water, solvents or packaging.

C. Ideal-typical re-utilization cycles for each process

In this chapter, the ideal-typical re-utilization cycle gets introduced. The three types of waste of each process get assigned to the introduced categories reuse, recycle, recovery and disposal. In all categories but disposal, material gets used somehow else again, whereas disposals get transported to landfill. Each process of a value stream gets layers for the re-utilization categories (see Figure 8). One specific re-utilization cycle then consists of five transport activities, three buffers and the re-utilization process itself to become an ideal-typical re-utilization cycle. This ideal-typical re-utilization cycle is applicable for all kinds of production/assembling processes. An example to illustrate is an injection moulding process. Due to set-ups, sprue and scrap rate waste is created to produce

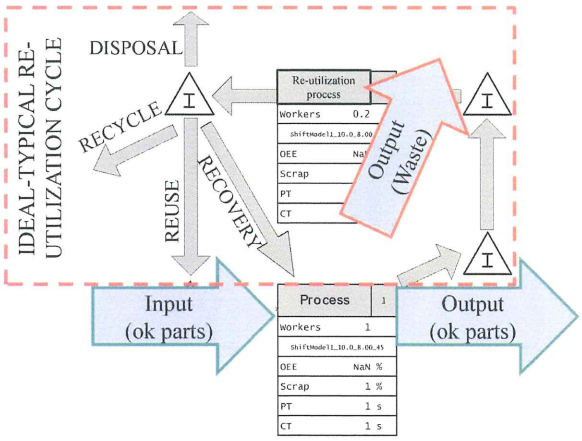


Figure 8. Principle of an ideal-typical re-utilization cycle.

customer demand; 80% of total waste is recycled to produce other products (e.g. a linoleum covered floor) and 20% is disposal so we have two layers. The machine operator puts all types of waste into one or more containers, which get transported by forklift to a silo for shredding. After shredding, the ready-to-recycle material waits in bags on a pallet. All efforts like space, transport distance and time for re-utilization can be assessed similar to classic VSM approach. Furthermore, one can separate between several resource types in value stream to distinguish types of disposals. On the one hand, this modeling of resource flows at processes seems not replicable when drawing value streams with paper and pen, but on the other hand it is suitable to be represented in a VSM software tool. Figure 8 shows system boundaries and layers of an ideal-typical re-utilization cycle of a process in a value stream.

D. Calculation of sustainability indicators and disposals data line

Applying ideal-typical re-utilization cycles at processes of a value stream enables the calculation of sustainability indicators such as disposals by the presented model. This model can then be applied to calculate waste and disposal for all resource types in the same way. Practical examples next to primary input resources are solvents, drinking water, process water and packaging materials. Finally, all criteria needed for sustainability and/or customer reporting can be calculated in the same way with the presented model. When calculating total lead time of a value stream, all waiting times in buffers are added; same when calculating total process time with adding up all process times in processes. These two values are represented in the time data line at the very end of a value stream. We use the same approach for the disposals data line. All types of resource disposals are summed up to calculate the total disposals value. As an example to illustrate, a specific value stream consists of four serial processes and the process technologies are injection moulding, painting, assembling and sequencing. Types of disposals of primary input resources are therefore synthetics, coating and parts from bill-of-material in unit kilogram per part. Other resources may be solvents and process water at coating process as well as cardboard and synthetics of packaging material at assembly process. All categories of disposals can be summed up apart from each other and/or altogether to represent the disposals of a whole value stream. The final disposals data line of a value stream is shown in Figure 10; sustainability indicators are calculated per part to be comparable.

E. Data Model and Calculations

This section describes the data model used in VASCO and discusses some implementation aspects.

1) Graph Structure: Naturally, the elements of a drawn value stream map correspond to a graph structure. Generally, a graph $G = (N, E)$ consists of a set of *nodes* (or vertices) N together with a binary relation E on the set [52], each two nodes whose relation evaluates to true are called *connected*, and such relations are called *edges*. If the edges have an associated direction, the graph is called a directed graph.

Our design rationale for a consistent data model for a VSM map is a graph that represents all aspects of the map. Therefore, each concept of a VSM (e.g. a process or a flow) is represented by a node $n \in N$ in the graph, relations between VSM concepts are represented by a directed edge $e \in E$ between the corresponding nodes. Each node, or concept, contains a set of named properties. Each property is associated to a value, which can either be **fixed**, i.e., the value is entered as a numerical value, or **calculated**, therefore, it depends on the values of other properties, in some cases even from other nodes. Edges in this data model do not contain properties. We call this data model the *concept graph*.

2) Evaluation of Calculated Values: Naturally, the dependencies of calculated values impose an ordering on the evaluation of such values. One could implement such an ordering by assigning priority values to properties under the assumption that all dependencies will be correctly handled if the nodes are evaluated in priority order, however, all nodes would have to be re-evaluated if a value changes, which is

- slow, as many values will be recalculated even if they do not depend on a changed value which is a problem especially for larger graph, i.e., a scaling problem
- error-prone, as the implementation has to make sure that the assumption holds, i.e., changing one formula may require to change priority values of many other formulas

Furthermore, while such constraints can be maintained without much effort for some calculations, e.g., one value of a concept depends on another value of the same concept, there may exist more complicated dependencies, e.g., one value depends on another value of all concepts of type process.

Our solution to this problem is to represent the dependencies of calculated values in an additional graph structure, the *dependency graph*, which allows to re-evaluate just the dependent values if a value is altered. An example can be seen in Figure 9: the main VSM structure is encoded using the blue rounded rectangle concept nodes (e.g. Buffer) and black dashed edges. The nodes of the second graph consist of properties of VSM concept nodes, represented by green elliptic nodes, the dependencies of calculated values are represented by blue dotted edges. Dependencies are encoded as influences, i.e., each value points to all values that depend on it in their calculation.

First experiments implemented this second graph structure, the *dependency graph*, explicitly. However, this approach did

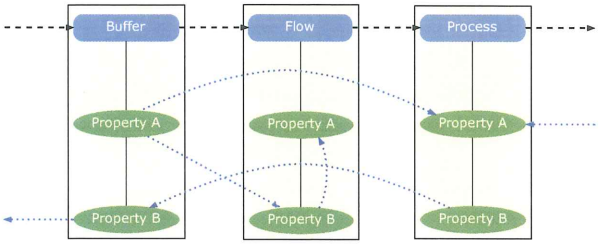


Figure 9. The data model of VASCO captures the structure of the VSM graph.

not scale well as all structural changes to the VSM graph also need to be propagated to the dependency graph. Therefore, we propose a meta representation for any calculated value in the system that separates dependencies from calculations

- an *identifier* function that identifies all *dependent* nodes of a given concept graph, and
- a *evaluation* function that performs the actual calculation reading the values from identified nodes and returns the calculated value.

These two methods help for an efficient evaluation, as there are situations where the dependency information depends on a concrete concept graph structure (e.g. dependency on all concepts of type flow). In these cases, the dependencies and consequently the calculation will change if the concept graph structure changes.

Using the identifier function, the dependency graph can be built straightforward: For each calculated value, its dependencies are determined using the identifier function, each dependency is mapped to an influence edge in the dependency graph. In our implementation, the dependency graph is rebuilt on each structural change of the concept graph. We call the complete dependency of a value, i.e., all dependent values, and their dependencies and so on, the *influence hierarchy*.

If the user changes a fixed value using the VASCO GUI, the influence hierarchy is identified via a graph traversal (e.g. breadth-first search or depth-first search) of the directed dependency graph, starting at the changed value. Thus, the traversal also yields the correct ordering for evaluation, and all values are re-calculated by calling the evaluation function for each node of the traversal.

V. Use Case: Assessment of Disposal and CO2 in Value Stream

The following use case is based on a simplified example from the automotive supplier industry, which has been extensively modeled and evaluated in practice. To reduce complexity here, a simple serial value stream is selected. The described process chain is represented by 'thermoforming', 'injection moulding', 'welding', 'assembly' and 'shipping' (see Figure 10). It should be noted, that the process steps, their sequence and frequency as well as the present conditions of process parameters are fictitious. The contemplated automotive supplier manufactures modules for various OEM, the production of side interior door panels has been selected as the product family.

A. Input of related resource consumption in VASCO

By opening the properties of the process shapes, the user is able to input relevant resource consumption to calculate the **disposal** and **CDE-value** per part. Due to the use of resources and the three types of waste, for each process the share of disposal can be calculated. Here the disposal is 0.25 kg per part, which is entered into the input mask (see Fig. 11 Input of Disposal). Measures to reduce disposal share may be, for example (a) allocating the waste to one of the other types reuse, recycle or recovery or (b) reducing the total waste by investing into new processes or design changes.

Next, the resource consumption to calculate the CDE-value per part are entered. In this use case these are direct input of energy resources as 'energy intensities', which can be measured at the process (equals '2. Energy direct' Fig. 4). At the selected process thermoforming, 3 kWh electric energy input per part is entered into the text field 'Electricity'. Furthermore, energy input values of the infrastructure (indirect), for example lightning, heating/cooling and compressed-air, can be entered. In practice, this is done by measuring these values directly at the process. Indirect energy input values are measured, e.g., at the circuit breaker panel and assigned to processes and buffers by allocation dependent on space. As a result, additional calculations apart from VASCO are needed, which are very extensively in practice. The situation is similar to the elements 'buffer' and 'transport'. Furthermore, the traditional aspect of VSM should not get lost, so certain simplifications have to be made when input indirect energy consumption, e.g., for lightning, etc. Nevertheless, the significance to management is still given.

Therefore, it is required for buffers to collect and enter all energy input values in VASCO. For transports, only direct energy inputs are gathered; the indirect energy input value of the needed space cannot be assigned to a specific product family. To avoid inaccuracies, it is recommended to assign the indirect proportion of transport to the inventory space. In Fig. 5 the input mask for transports and stocks is displayed. Here the user enters the total energy consumption for current (0.0230 kWh per part), gas (0.01 kWh per part) and compressed air (here: none).

The ideal-typical re-utilization cycle, which has been defined in section 3.3, is assessed by analogy with the previously presented elements in VASCO value flow (see Fig. 14). First, for each recycling category (here: Reuse), the energy-input-values in kWh are entered in the period of customer requirements (for example, per shift or working day). Following VASCO calculates the energy inputs per manufactured good part and also the Carbon Dioxide Equivalent (CDE). The conversion is explained in the following chapter.

B. Entering the conversion factors for CO2 assessment as CDE-value

VASCO has a tab 'CDE' in the general VASCO properties in which, among other cost rates, shift patterns and transports can be defined. These unique requirements apply to the entire value stream, so that the energy inputs for electricity, gas, compressed air and other resource inputs, such as solvents, can be entered.

The values entered here are location-specific conversion factors, which for example depend on the energy mix of the electricity supplier or the chemical composition of the solvent. Here, the CDE conversion factors for current (0.43 kg CO2 per kWh), gas (0.18 kg CO2 per kWh), compressed air (0.2 kg CO2 per kWh) and solvents (1.22 kg CO2 per kWh) are

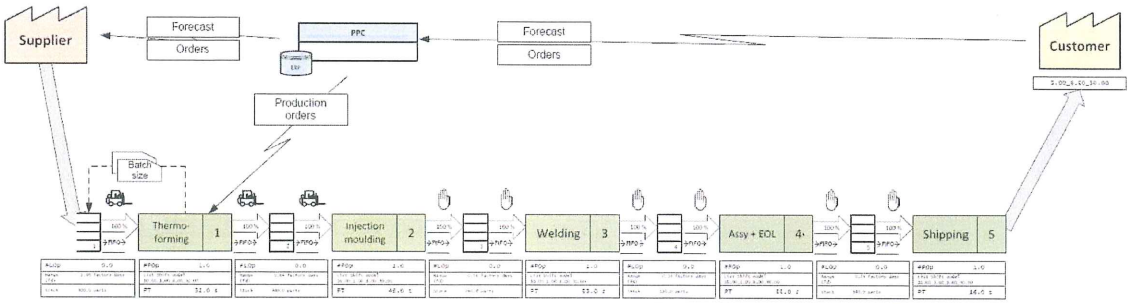


Figure 10. Input of resource consumption to calculate disposal per part

Resource Management | Waste Management

Type of resource	Resource type(s)	Batch Size [part (s)]	Net demand per part [kg/part]	Gross demand per part [kg/part]	Waste per batch [kg/part]	Calc [kg/part]	Disposal [%]
1st Primary	Synthetic materials	1 part(s)	0 kg/part	0 kg/part	0.25 kg/part	0.25 kg/part	100
2nd Primary		1 part(s)	0 kg/part	0 kg/part	0 kg/part	0 kg/part	0
3rd Primary		1 part(s)	0 kg/part	0 kg/part	0 kg/part	0 kg/part	0

Figure 11. Input of resource consumption to calculate disposal per part

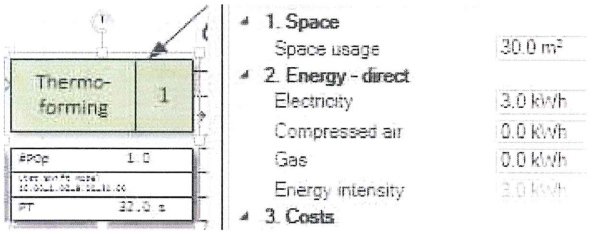


Figure 12. Input of the direct energy consumption of a process in VASCO

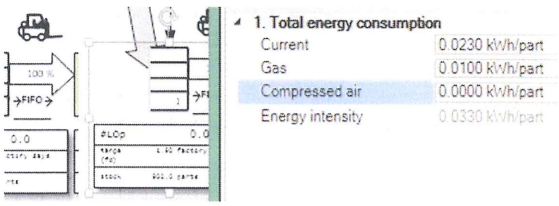


Figure 13. Input of the energy consumption at the VSM elements 'transport' and 'buffer' in VASCO

values according to the energy contracts of production site entered by the user in VASCO.

C. Displaying the CO2 assessment in value stream

The CO2 assessment of production is done through accumulation of direct and indirect energy inputs over the entire value stream that is, for all processes, transports and stocks / buffers and subsequent conversion to the equivalent CO2-value (CDE) per produced part. It should be noted that total energy consumption is calculated by number of good parts (here: D_{net} - cp. Cumulated scrap rate) produced and shipped to the customer.

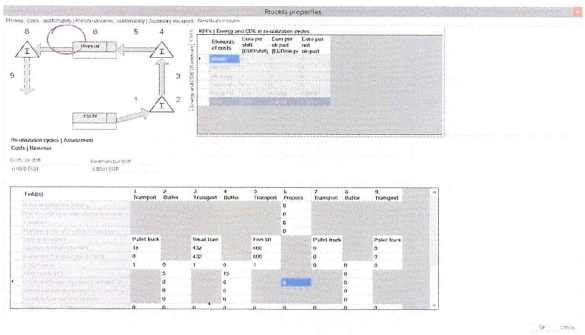


Figure 14. Energy consumption and CDE assessment in ideal-typical re-utilization cycle (here: Reuse) in VASCO

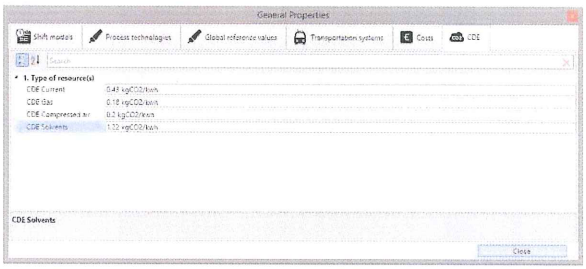


Figure 15. Input for the CDE conversion factors in VASCO

D. Visual representation of the value stream in VASCO

The following figure (Fig. 17) shows the holistically analyzed value stream with focus on time, disposal and CDE-value. This visual representation of the value stream deposited with meaningful and generally accepted indicators makes it possible to search specifically for potential improvements in resource use and derive the best possible improvement measures. In addition, further possible measures can be evaluated in a secure laboratory situation to support investment decisions

Process | Direct	
1. kWh/ok-part	
Solvents	kg/ok-part
Current	10 kWh/ok-part
Gas	0 kWh/ok-part
Compressed air	0 kWh/ok-part
Sum	10 kWh/ok-part
2. Caused CDE	
Solvents	kgCO2/ok-part
Current	4.3 kgCO2/ok-part
Gas	0 kgCO2/ok-part
Compressed air	0 kgCO2/ok-part
Sum	4.3 kgCO2/ok-part

Process | Indirect	
1. kWh/ok-part	
Current	1.2 kWh/ok-part
Gas	1.2 kWh/ok-part
Compressed air	0.8 kWh/ok-part
Sum	3.2 kWh/ok-part
2. Caused CDE	
Current	0.516 kgCO2/ok-part
Gas	0.216 kgCO2/ok-part
Compressed air	0.16 kgCO2/ok-part
Sum	0.892 kgCO2/ok-part

Figure 16. KPI overview with focus on CDE-value per good part (accumulated over whole value stream)

on a resilient basis. The upper data line is the traditional time line indicating the ranges of each stock / buffer compared to the total time of the processes. The middle data line displays the disposals in kg per good part (here: ok-p.) that occur at every process. The values at the right show the sum of disposals of every process, while T-DISP is the total disposal including packaging. In this use case, these are 0.25 kg per part, while no disposal for packaging occurs. The lower data line represents the CO2 assessment along the value stream. The upper stairs correspond to the direct energy consumption in kWh/part, the lower stairs are the sum of direct and indirect (structural) energy consumption per part (here: good part which leaves the process). The arrows in opposition to the direction of material flow are for the energy consumption in the ideal-typical re-utilization cycle. In this example use case 5.2486 kg CO2 per good part (here: ok-p.) are emitted as carbon dioxide equivalent (for electricity, natural gas, compressed air and solvents) into the atmosphere.

VI. The Role of Simulation

The ultimate goal of lean manufacturing is to reduce waste in human resources, inventories and time to market [30]. This allows a company to be more responsive to customer demands, while producing high quality products in an efficient and economical way [53].

Value Stream Mapping (VSM) is one important principle in lean manufacturing, because it provides understanding on how product and information flows affect each other. Traditionally VSM only provided a static picture of a process, but not in our VASCO VSM tool. VASCO VSM allows the user to see where value is added into the value stream, and calculations can be performed automatically. Through the adding of additional simulation capabilities, we can now evaluate behavioral issues of processes.

With lean manufacturing and VSM, the company can easily recognize and eliminate sources of waste. It is visible how each operation contributes to the whole, so that change decisions can be made when bottlenecks exist. It provides the ability to visualize information and product flows, and it allows the study of where, when, and how waste occurs. The implementation of lean principles involves applying concepts like Kanban, layout planning, visual control, and takt time calculations [54]. There are several reasons why waste usually occurs, and they are well described in the literature [55]. These seven types of waste are: over production, unnecessary inventory, long waiting (e.g. including long inactivity and lead times), excessive transportation, defects (e.g. in materials, causes rework or quality problems), ineffective motion (e.g. process not well designed), and inappropriate processing (e.g. due to wrong set of tools, in procedures or in systems).

The integration between VSM and simulation improves processes in general, because it makes visible both the static and the behavioral characteristics of a process [30].

A. Simulated Guided VSM – Design Approach

Firstly, VSM is usually applied as part of the lean production tools portfolio. It highlights process inefficiencies, transaction and communication mismatches, and it also guides improvement areas.

Secondly, simulation is used to reduce uncertainty and create common and justifiable overviews. This is done by visualizing dynamic processes. It is a complementary tool for VSM because it provides the quantifiable evidence needed to justify a lean approach. A simulation model is developed to replicate the operation of the existing system, and also the improved future system which should modify or replace the current implemented system. This is done with the objective of incorporating better lean principles.

Usually, the approach [30] is to construct a comprehensive model for the manufacturing process. Distinct scenarios are derived to uncover an optimal future state of the process, according to the VSM analysis. Various simulation scenarios are then developed. The simulated results are acquired and investigated, and they are matched against real production data to verify the respective model accuracy.

Simulation is therefore a guiding tool to assist organizations with the decision to implement improved lean principles. This is achieved by quantifying first the benefits of applying VSM. Then, a road map is created to help illustrate how VSM can be used to design the future states. Lastly, the developed simulation scenarios mimic the real behavior of past and future manufacturing processes.

B. Considerations on Applying Simulation

Like stated before, VSM has been traditionally viewed as a paper-and-pencil exercise. Several paper drafts (digital format in VASCO), are developed to answer specific questions on efficiency and technical issues related to lean tool implementation [56].

However, sometimes the future state map cannot be designed just by having an idea of what to change. The prediction of inventory flows and levels, is not feasible only with static data. Most traditional VSM applications do not use simulation, because in the past these required a long preparation time and effort. The development of a useful simulation model tended to be a lengthy process, which required thoughtful validation (i.e. experiments and statistical data). Usually, this development was also not well aligned with the quicker cycle time needed for manufacturing.

Nowadays, simulation is sometimes seen as not worth of the additional time and money investment. When simulation models are developed and well validated, the company gets trusted statistical data which will be valuable for the optimization of future states. Nevertheless, in today's world, simulation is also used as a way to reduce uncertainty and to create a common view. It helps explore alternatives generated by different responses to VSM design questions. If simulation is

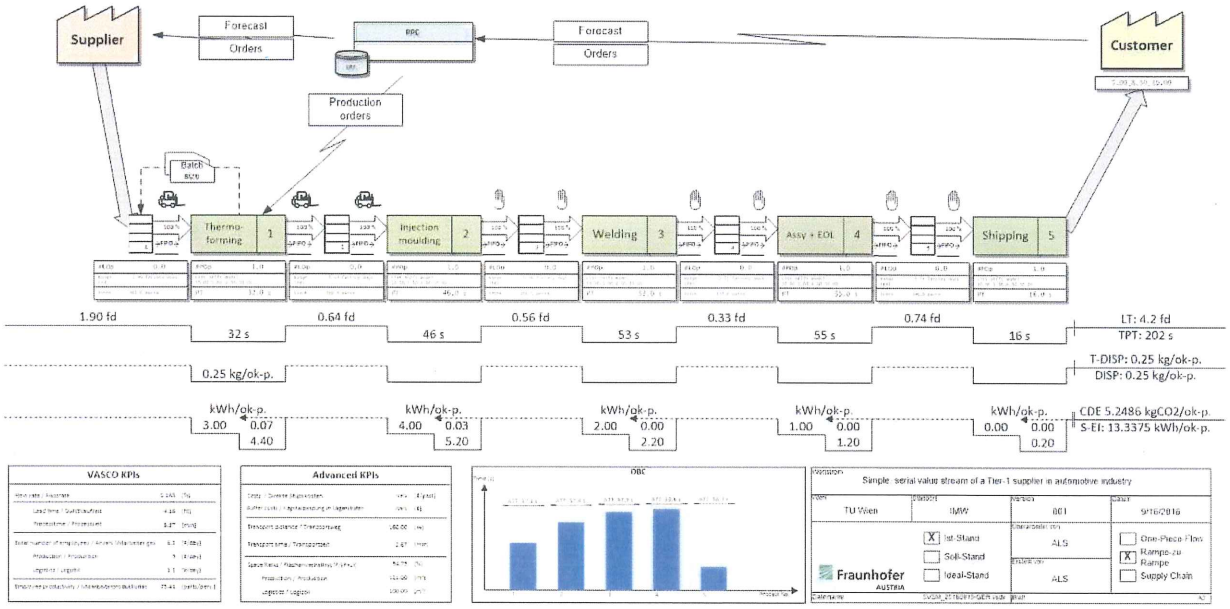


Figure 17. Representation of a holistically analyzed value stream in VASCO with data lines Lead Time, Disposal and CDE

integrated into a VSM tool, it can be flexible and robust to detail changes in VSM.

C. Creating a Common View Through Simulation Guided VSM Work-flows

According to previous work in this field [30], a key problem in getting everybody to a common view is related to the absence of visual depictions, i.e. the ability of being able to explain to others about the current state dynamics. After this challenge, comes the inability to communicate an action plan that can be understood by all stake-holders. To this end, VSM and an integrated simulation tool can definitely help in visually capturing and demonstrating current and future states that can accommodate changes.

A value stream is a collection of actions (both value-added and non-value-added) required to produce a product or product family, which uses the same resources, starting with raw material and ending with the customer [57]. The VSM is defined as "the simple process" of directly observing the flows of information and materials as they currently occur, visually summarizing them, and then envisioning a future state with much better performance [53]. The primary objective of the VSM is to identify all kinds of waste in the value stream and to take actions to eliminate these [56]. Researchers have created many lean tools to optimize individual operations. However, most of them fail in providing a clear visual representation of the material and information flows throughout the entire process [58]. The VSM creates a common base for the process, thus facilitates more thoughtful decisions to improve it [59]. This helps plan and link lean initiatives through a systematic data capture and analysis. The VSM has emerged as the preferred way to implement lean principles, inside facilities and at the supply chain level [60].

Sometimes, management decisions rely only on external results and expected benefits reported by VSM implementations external to the company. However, this is always an insufficient justification, and lacks the quantifiable evidence needed to convince to adopt lean principles [61].

VSM was literally drafted by answering specific questions on issues related to efficiency and on technical lean tool implementation [56]. In some cases, however, the future state map cannot be designed by solely using static data. For example, predicting the inventory flows and levels is impossible having only static data.

Developing a useful simulation model tended to be a time consuming task, not well aligned with the relatively quicker cycle times. However, simulation as a process simulation model, is often used to reduce uncertainty and create a consensus view. This is done by visualizing dynamic process views for a given future state. Additionally, it helps explore alternatives generated by different responses to those design questions. Simulation is capable of generating resource requirements and performance statistics whilst remaining flexible to specific organizational details.

Simulation has been considered as one of the most flexible analytic tools in the manufacturing system design and operation areas. It is used to handle uncertainty and create dynamic views of lead time and machine utilization. This enables quantification of results, and provides a possibility to compare the expected performance relative to that of the present one. Thus it can be used to assist organizations with the decision to implement the VSM, by quantifying benefits from applying lean principles in their specific situation. The majority research in this field describes the use of simulation to analyze existing or planned manufacturing systems.

Value stream mapping simulation is useful also for value stream mapping training. Each process has a defined cycle time. These cycle times are not the same, and because the work cells are interlinked, inventory builds up in between each cell. One can change many parameters, such as: cycle time, up time percentage, number of shifts, or the total available time,

for each station. This is where the simulation comes into play, e.g., by simulating the first stations with a fast processing time, and the last station with slow times, we get as a result a "ton" of inventory in the middle (bottleneck). Parameters can also be entered based on group's discussion. The group can flip back and forth between the simulation and the VSM, to check how changes affect the simulated processes.

D. Value of Simulation and the Future State of VSM

Here, we refer again to the seminal work of Wei Xia and Jiwen Sun [30], where the authors give clear explanations on the value of having a simulation guided VSM work-flow. In both VSM and simulation, many "what-if" scenarios can be tested and a choice is made regarding the optimal one(s). These scenarios have distinctive key points, like the addition or subtraction of machines, and balancing of work shifts. The simulated results are used to understand accumulation of work-in-progress (WIP) before and after each process, e.g., to compare a machine efficiency or to properly account for variability. They are utilized to balance throughput, WIP and production lead time. The simulation model is a general tool for future shift, product mix and expansion decisions. Being able to achieve a higher production volume and fulfill the demand of the customer within shorter lead times is a great marketing advantage. Driven by these simulated results the company modifies the layout plan and the future state diagram.

The so called, simulation guided VSM [30], allows the management to distinguish between value added and non-value added activities. It has the potential to be a strategic decision making tool for process redesign and continuous improvement. With detailed information obtained from the simulation guided VSM, it is for example possible, to determine if cost savings or increased revenues can be made with additional capital investment.

For the operational staff, implementing simulation guided VSM can be more convenient, interactive, and straightforward than the traditional paper-and-pencil based VSM.

VSM is not always sufficient to describe the current state of a manufacturing process and design a desired future state. Simulation is then utilized to enhance but not replace the VSM by visualizing better dynamic features of the future state before implementation. Different simulation scenarios are developed by observing the actual processing times of activities in the manufacturing process and then characterizing their variation by statistical distributions.

Simulation also adds a fourth dimension, i.e. time, to the value stream map. After being simulated, the VSM is no longer just a snapshot. VSM is now a moving picture, which offers insights that may have been missed if only VSM alone had been used. Simulation of the VSM allows the lean team to quickly implement try changes, without interruptions in the production processes.

VSM is a valuable tool in lean manufacturing and in the continuous improvement effort. Simulation makes testing ideas easier, cheaper, and quicker, and gives an immediate assessment of the future proposed changes to the system. The VSM process provides the model and the data, making it easier to prepare and perform all the simulation work. Therefore, VSM and simulation complement each other very well.

E. Integration of VASCO VSM with Process Simulator

In VASCO, we developed an integration between the act of preparing VSM state diagrams, and a process simulation application called, ProModel - Process Simulator [62]. The main goal is to provide a simulation function from within our VSM tool VASCO. Besides the usual visualization and calculation of production processes, our partner manufacturing companies, also expected the development of a simulation function. This function should contribute to a significant increase in quality results of the production process analysis, Which allows to check important parameters, such as:

- Process capacities
- Buffer capacities
- Overall output in a certain period of time

We based our decision for the selection of the simulation tool (ProModel – Process Simulator), on the analysis of some of the following requirements:

- a discrete event simulation of manufacturing processes
- the user interface used to transfer data between VASCO VSM and the simulation tool, should be easy to use
- the tool should have a strong credibility in automotive industry, as well as in other industries
- require a minimum amount of integration and programming effort
- low costs involved in terms of licensing
- support MS–Visio and Excel import/export functionality
- integrate the VSM data directly into the simulation
- include batching/un-batching, shift models, routes and resources, order system and dispatching rules (FIFO, LIFO, percentage, conditional)
- clear and visually appealing results (include parameters like: throughput per day/shift, process utilization, waiting and blocking percentage and visualization capabilities, i.e. histograms and other charts)
- allow to compare multiple scenarios and allow for multiple runs with different distributions (accurate results)

We considered feedback from several partners which are experts in applied VSM and simulation of processes. The company ProModel helped, by providing development licenses for our integration development. Process Simulator proved to be efficient by fulfilling all the major requirements of our partners. Manual and automatic integration between VSM and the simulation was developed. The automatic integration allows users to transfer bi-directional data between VASCO VSM and the simulation tool. Nevertheless, the users are still able to manually edit and transfer all the VSM and simulation parameters if necessary. It was necessary to introduce in our tool minor modifications regarding the automatic exit representation of process scrap, as required by the simulation tool (Figure 18).

Many other parameters (e.g. buffer capacity analysis) will be available during the final integration version between VSM and Simulation.

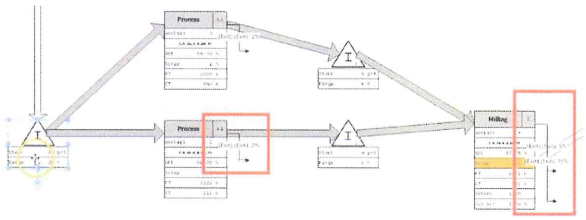


Figure 18. Simulation prototype: scrap-exit per process represented by new percentage arrows (inside red squares).

Figure 19. Example results (red squares) obtained from our VSM-Process Simulator integration. Histograms show expected capacities/through-puts of buffers and processes. In (1) we can observe the work unit results. In (2) the different processes and buffers percentages (operation, setup, idle, waiting, blocked, down). In (3) the total number of product produced and average times.

In this work we present preliminary results obtained in our simulation prototype tool. It is not yet a full implementation with Process Simulator (Figure 19).

The integration between VASCO VSM and Process Simulator has multiple benefits. Firstly, there is no need to manually exchange VSM parameter' values between a separated VSM tool and a simulation tool. These steps are now fully automatic and integrated in one tool. Secondly, users with different levels of expertise in the manufacturing site or on-training, can now experiment with both tools (VSM and simulation) in an integrated way, and try out different scenarios. Users can now test real changes very quickly and experiment while learning about VSM and lean manufacturing. Thirdly, multiple scenarios can be tested, leading to an optimal definition of the VSM future state.

VII. Future Work & Conclusion

With VASCO it is possible to use only one tool throughout the complete work-flow of value stream analysis. It dramatically simplifies the data acquisition at the shop-floor and offers a large tool set for analyzing and improving the production/logistic value chain.

Also the extraction of production metrics can be done at any stage of the work-flow creation, allowing the users to immediately have calculations feedback about the impact of their changes when designing future state maps. Lastly, by using our tool the users can capture information along the entire value stream analysis process, starting with visits to the production sites, where the users can capture images and videos of the working processes as side annotations, up to the creation of a new diagram based on previous processes work-flow states with comparisons between multiple state realities of the existent manufacturing processes, where the users can still access all the annotated information about old and current manufacturing processes. The integration of sustainability criteria within a VSM will significantly help manage and reduce the amount of waste, resulting from the manufacturing processes. This provides new metrics and KPI's that help to capture each company production reality in a digital way.

One minor extensibility limitation is that calculations are coded into the core system. While we are able to supply new functionality to the users using the plugin system, we plan to enable the definition of any type of calculation to the end user This definition should be flexible enough to handle all types of calculations, but simple enough without the need for complex programming tasks. This will be achieved by using a domain specific language (DSL) for calculations that contains important abstractions for the specification of VSM concepts.

Another important aspect is the integration of continuous improvement routines like CIP in VSM and VASCO, that will significantly help manage and reduce several types of waste (MUDA), resulting from the manufacturing processes. This will also provide new ways to improve metrics and KPIs of VSM

User experience is always a primal focus in all industrial applications. We are planning experiments where the users will perform fundamental tasks with our tool. With the help of an eye tracker equipment we will record data about the way users perform their tasks and about their individual preferences.

It is our intention to assess how our tool is used in reality by the final users and to study it's usability. We expect to be able to use this data to improve the overall experience of the users and as a way to boost the productivity of the users when working with our tool.

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