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Problems of System Dynamics model development for complex product manufacturing process

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Abstract. Computer simulations are applied in enterprises for different purposes. They are used to support decision making at different levels of management. System Dynamics (SD) method is successfully used to model and simulate complex systems (including enterprises and manufacturing lines), but its applications are limited mostly to the policy and strategy level. This is due to the fact that SD approach assumes a low level of details and perceiving the system as a whole, and on the other hand, the reason may be the lack of examples of modelling manufacturing lines and workstations, at a higher level of detail. Based on a case study of a complex manufacturing system, this work presents examples of SD models of workstations and manufacturing line elements. Problems that were discussed in the frame of this paper are: process discretization, information flow with the use of kanban cards, processing of various components in one process, work of many employees at one workstation and assembly kit completion. The presented work may encourage researchers to use SD to model and simulate manufacturing lines at the operational level, and the presented solutions will be used in industrial practice to analyse and improve production systems.

1. Introduction

Simulations are useful in supporting decision making process. By simulations applied in manufacturing process analysis, possible results of different changes can be easy discovered. However, still many manufacturing companies do not implement computer simulations. Many reasons of this situation can be identified. Among them the following can be distinguished: lack of knowledge in companies to create simulation models and then perform simulation experiments, manufacturing systems complexity what makes the model creation process time consuming

Currently, simulations are already applied in many companies. Also, many publications present possible applications of computer simulations. There are different methods and tools which can be used to simulate manufacturing processes. One of the widely used simulation methods is System Dynamics (SD) developed by J. Forrester. The system is defined in SD as a collection of elements that interact with each other over time, forming a unified whole. Therefore, SD is a method used to describe system performance over time. SD describes the behavior of system components using differential equations. Due to the nature of these mathematical functions, the SD method is well suited for modeling continuous systems.

In SD method, components and relationships between components form the system structure. The basic idea of SD says that the structure of the system determines its performance [1]. The structure of the SD model consist of two basic elements, i.e. stocks and flows. The stock represents the state of the indicated system element, usually where the resources are stored. A flow is an input or output stream that governs stock fluctuation. In the SD model, the factors affecting the system behavior are reflected in the form of cause-effect relationships and feedback loops.

Many examples of the use of SD models for manufacturing systems analysis can be found in the literature. The basics of SD applications in simulation and modeling of manufacturing systems were provided by Forrester [2], who introduced the model of the production and logistics system. Edghill and Towill [3] modeled manufacturing systems, taking into account the flow of information and materials. The effectiveness of manufacturing lines with the kanban cards was deeply investigated by Byrne and Roberts [4]. Stadnicka and Litwin [5, 6] proposed the use of value stream mapping (VSM) to build the detailed SD model of the manufacturing system. In [7] the combination of SD with Discrete Event Simulation (DES) for manufacturing system performance evaluation was shown. Mahmood [8] uses the SD model containing selected Lean elements as a tool for planning and assessing the impact of financing on the overall profitability of the company. In the work [9] SD approach was adopted for real-time production planning and control system for job-shop manufacturing. In the review paper [10] it was shown that SD is extensively used for modeling and simulation in many industries, including: extruded food production, aircraft manufacturing, automotive, logistics, electronics, software development and computer hardware.

Despite such a wide range of SD applications, it should be noted that in the vast majority of cases the cited SD models are used for system analysis at the policy and strategy level. This is due to the fact that the SD approach assumes low level of detail reproduction due to aggregation of system elements. According to this approach, the manufacturing system is presented as a "black box" described by a formula depicting the relationship between its input and output streams.

An example of an alternative approach is DES, which is widely used to model discrete systems at a high level of detail. DES models, however, more often reflect systems in which units are processed in a linear manner. Unlike SD, DES is less focused on identifying cause-effect relationships, in particular feedback loops, that may cause changes in model parameters and affect the system's operation in the long run. The most important differences in the DES and SD approaches are shown in [7].

The goal of this work is to present how the SD approach can be applied to model a manufacturing process at the detailed level. Based on a case study, the following problems are discussed: flow discretization, implementation of the pull system, assembly kit completion, processing of different elements in one process and work of two employees in one process. The presented examples may contribute to the increase of SD applications in the analysis of manufacturing systems at the operational level.

In this work the authors discuss development process of a system dynamics model created to analyse performance of a manufacturing line on which complex product is manufactured. In the frame of the work, first, the manufacturing system is presented. Then, important issues which make the system complex and complicated are discussed. Next, the overall structure and details of the SD model, which can be used to simulate the analysed manufacturing system performance. The problems which appeared in model development are discussed and the problem solutions are presented. Finally, a list of recommendations is created.

2. Research problem and goal

The problem analysed in this paper concerns development of detailed System Dynamics Model (SDM) for complex product manufacturing line. An element of the innovation of the presented approach is to show how to use the SD method to model and simulate manufacturing processes of a complex product at the operational level, accurately depicting the material flow. The goal is to develop solutions for the problems which exist in manufacturing line on which complex products are manufactured. Moreover, the line is working in pull system. The SDM developed with the use of the presented solutions can be applied in performing different simulations. The simulation model created with the use of SD will allow for feedbacks implementation. Feedback loops are used to represent movements of kanban cards along a pull system.

The main results of the work are connected with a set of recommendations which can be used in SDM developed for complex product manufacturing line.

3. Work methodology

Work methodology consists of the following steps:

Step 1. Analysis of a manufacturing line on which a complex product is manufactured.
Step 2. Identification and analysis of problems which can make difficult a simulation model creation.
Step 3. Identification of possible ways of presentation in SDM of certain elements of the manufacturing line.
Step 4. Problems analysis and development of proposals for the solutions representation with the use of SD.
Step 5. Presentation of the solutions with the use of formulas which will be applied in SDM.
Step 6. Graphical representation of the solutions in Vensim software.
Step 7. Reference to fragments of Value Stream Map (VSMap).
The listed steps were implemented and presented later in this work.

4. Manufacturing process description

The complex product manufacturing line which is analysed in this work is described in details in the work [11]. The processes realized in the frame of the analysed manufacturing line (ML) are presented in Table 1 together with important data. Moreover, the graphical scheme of the ML is shown in Figure 1. In Table 1 such information as name of the process and processing times needed to manufacture one piece (component/unit/product) are presented. While, in Figure 1 the sequence of the processes realized to manufacture the ready product and material/component/unit/product flow are presented.

The company works 2 shifts per a day. One shift has 27 000 seconds of available working time. The availability of workstations is 100%.

Five problems which can make difficulties with SDM development were identified and the related parts of ML are indicated in Figure 1.

Table 1. Data concerning processes realized on the analysed manufacturing line; PT – processing time.

Process	PT [s]	Process	PT [s]
1. Deburring I	180	11B. Turning IIIB	1 095
2. Bending	60	12. Turning IV	90
4. Deburring II	120	13. Milling	960
5. Shipment to a subcontractor	600	14A. Deburring IIIA	150
7. Turning I	360	14B. Deburring IIIB	180
8. Cutting I	78	14B. Deburring IIIC	180
9. Turning II	2 073	16. Welding	2 100
10. Cutting	2 040	17. Assembly of components	7 500
11A. Turning IIIA	1 095	19. Final assembly	6 300

The components (Figure 1): SE, OLI, GAS and RAD are delivered by a customer. The components: SCR, WAS, NUT, CAP and materials: BAR, PIP and STE are bought. Other components: BRA, TTU, MSL, TSL, HC, FL, CYL, BOT, TOP, EAR and PLA are manufactured in the company. Totally, the product consists of 19 components.

The manufacturing system consists of 19 processes which are realized to manufacture 11 components from 3 different kinds of materials (BAR, PIP and STE). Four processes are realized by external service providers (3E, 6E, 15E and 18E). These processes are realized by cooperators in one day time. Processes 11A and 11B are realized on one workstation by the same operator. Similarly, the processes 14A, 14B and 14C are realized on the same workstation by one operator. The assembly process is divided into two parts. In process 17 all manufactured components are assembled. In process 19 the other components (bought and delivered by the customer) are assembled to the product.

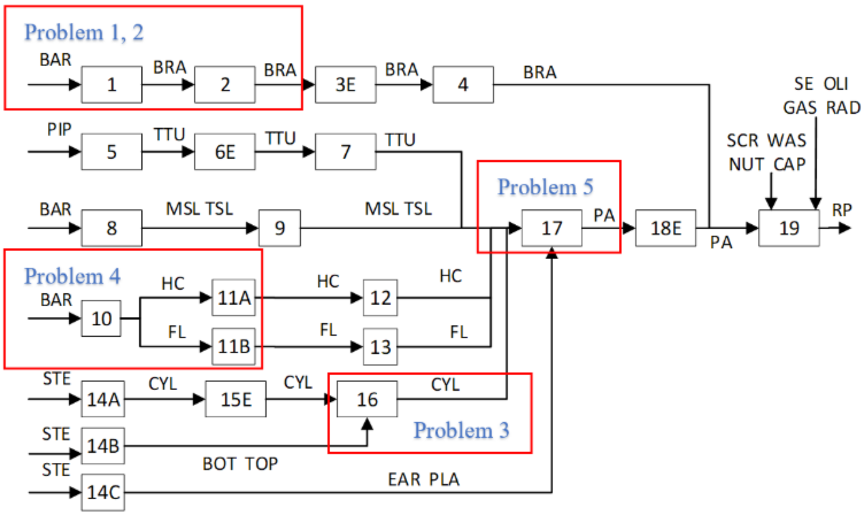

Figure 1. Manufacturing process structure with material flow.

5. Potential problems identification and analysis

Based on manufacturing system description the following problem which can make SDM development difficult are identified.

Problem 1. Processes discretization, i.e. transferring full pieces (elements, components). SD is a method of continuous processes simulation. This means that this method can be successfully used to model and simulate processes that are characterized by continuous flow between successive stages of production. Examples of such processes may be glass melting, refining liquid fuels, processing of loose products (e.g. flour, groats). In the case of the electromechanical industry, individual pieces or batches (of material, prefabricated elements, components) are usually transferred between successive stages (workstations) of the manufacturing process. In this type of processes (manufacturing line), the processing of a specific item in the next workstation may begin after the processing of this item in the previous workstation has been completed and that item has been delivered to the process. An illustration of the problem is shown in Figure 1 (Problem 1). The marked fragment contains the deburring operation followed by the bar bending operation. Bending may not start before the preceding deburring operation is completed.

Solution 1-1. Transferring the full piece (batch) at fixed time (e.g. multiple processing time). The production line model is constructed in such a way that individual processes perform processing only in calculated periods of time. The disadvantage of this solution is the need to synchronize often complex manufacturing lines in order to determine the working periods of individual workstations of the modeled process. For example, if the deburring time (1) is 180 seconds, and the bending time (2) is 60 seconds, then the first bending operation will start in 181 second of simulation, the next in 361 second, etc. In the case of delays in material flow (e.g. device failure, late delivery), the calculated period of operation of the device may change and the process will not be completed.

Solution 1-2. Discretization of flow by adding process input and output buffers to the model. The process retrieves material for processing from the input buffer and sends it to the output buffer. Material from the output buffer is transferred via the transport process to the input buffer of the next process. Material transfer occurs when the appropriate amount of material is available in the input buffer. The condition of sending the material may include additional requirements: the demand checking (information from the kanban card), the availability of free space in the next warehouse checking (e.g. the products may not have been picked up from the FIFO queue due to failures in the next process), the machine availability checking, checking if the time remaining until the end of the shift is sufficient to complete the process (applies to a situation in which the process cannot be interrupted and continued the next shift). Figure 2 shows a fragment of the manufacturing system model for the deburring (P1) and bending (P2) processes. The same fragment on VSMap is shown in Figure 3.

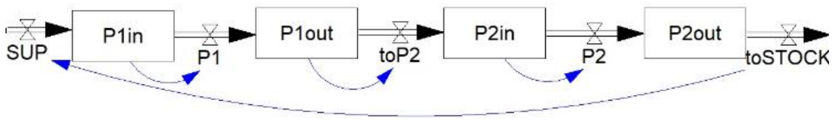

Figure 2. Model illustrating manufacturing discretization (flow of fixed portions of material).

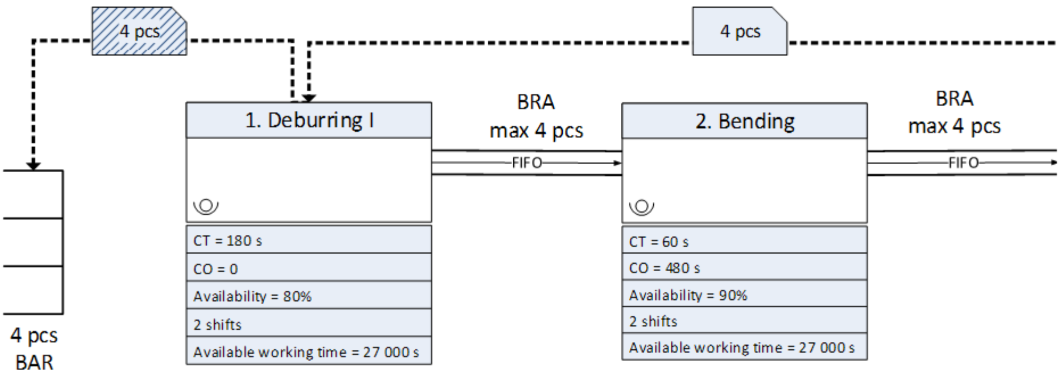

Figure 3. Part of the VSMap with a supermarket, FIFO queues and kanban cards.

Elements of the model presented in Figure 2 are: SUP – supply, P1in – in-stock of P1 (deburring), P1 – deburring process, P1out – out-stock of P1, toP2 – transfer process to P2in, P2in – in-stock of P2 (bending), P2 – bending process, P2out – out-stock of P2, toSTOCK – products leaving the model.

In the analysed case P1in acts as a supermarket. P1out, P2in and P2out perform the function of the FIFO queue. Formula 1 describes the material flow between P1out and P2in (transfer process toP2).

$$\text{IF THEN ELSE(P1out>=4, 4 , 0)} \quad (1)$$

According to the presented formula (1) if P1out contains 4 or more units, 4 units are sent to P2in, otherwise the transfer is not carried out. The reason for this is that the components are transferred between the processes in containers of 4 pieces. The material flow may additionally depend on the P2in status, e.g. material is sent when the P2in is empty. The formula describing the combination of the two conditions is (2):

$$\text{IF THEN ELSE(P1out>=4:AND:P2in=0, 4, 0)} \quad (2)$$

Problem 2. Transferring the production kanban card from the process from the bottom of the value stream to the process from the top of the value stream (upstream). The transfer of the kanban card is carried out as an information flow in the form of a feedback loop. Receipt of the production kanban card by the process is a signal to start manufacturing. To start production, the process must collect material from the supermarket. For this purpose, a transport kanban card is sent to the supermarket and the material is downloaded (Figure 3).

Solution 2-1. Figure 2 shows the dependence of the volume of supplies (SUP) on the number of units flowing from the production line (toSTOCK). Material supply is based on information about the number of products leaving the manufacturing line (or going to the next stage of the manufacturing process). This is how the pull principle is implemented in the manufacturing system.

Solution 2-2. In the case of complex models containing many elements in the SDM, instead of the line depicting the message of the kanban card the so called "shadow variable" referring to the source variable can be used (Figure 4). Many shadow variables can be used in the model. The disadvantage of this solution is that the model does not show directly the place where the kanban card was sent from.

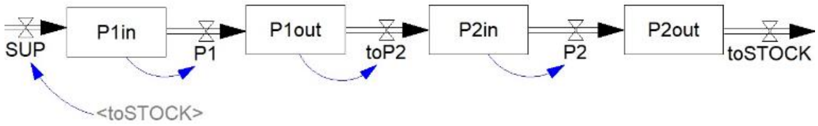

Figure 4. Kanban card flow represented by shadow variable.

Problem 3. The process of completing assembly kits is not shown on VSMap because it is merged with process 16 (Welding). In the process an operator picks up the components and assemble them. Modeling of the manufacturing system using the SD method gives the opportunity to implement and visualize the creation of assembly kits. Moreover, it is indispensable. To perform the assembly process all components have to be available and the assembly process cannot start when a component is missing. Therefore kits preparation process needs to be included in SDM.

Solution 3. The completion process is carried out between the outputs of the component preparation processes (at least 2) and the input of the assembly process (welding). The kit completion model is based on two-way communication between the receiving stock and stocks supplying components for picking. If the required number of units is available in each supply warehouse, an assembly set is created. At the same time, the inventories of the respective components are reduced by the appropriate number of units. The model for creating the assembly kit is shown in Figure 5. Figure 6 shows the corresponding VSMap fragment that presents the problem being analysed. Two FIFO lanes are added to the welding process (process 16): one from process 14 and one from process 15E.

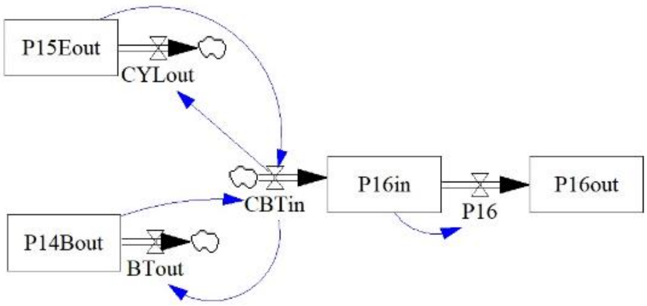

Figure 5. Model for creating the assembly kit from two components.

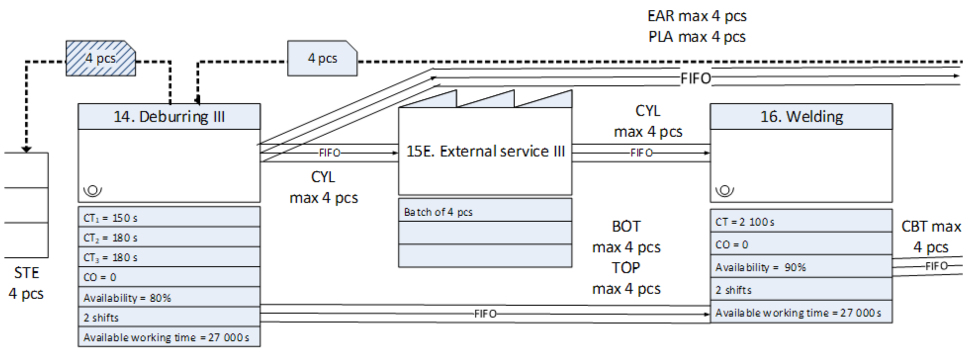

Figure 6. Part of the value stream map with a supermarket, FIFO queues and kanban cards.

Figure 5 shows the component stocks P15Eout (component manufactured in the P15E process) and P14Bout (component manufactured in the P14B process). CYLout and BTout output flows are connected to these stocks. P16in is a stock for assembly kits, whose input is the CBTin flow.

The CBTin flow formula is defined as follows (3):

$$\text{IF THEN ELSE(P14Bout>=4:AND:P15Eout>=4, 4, 0)} \quad (3)$$

According to (3), if both component stocks (P14Bout and P15Eout) contain at least 4 units, then 4 assembly sets are sent to the P16in stock. The flows in the CYLout and BTout are equal to the CBTin flow.

Problem 4. Processing of two or more types of components in the same process (in the same workstation). In SD, it is not possible to distinguish between types of components or the order of their processing in one process (flow). In a sense, this is a limitation of SD simulation. All types of products are sent to the same stock and are not differentiated.

Solution 4. If two components are machined in the process, first of all the equation of the process should be determined. For example, in the P10 process, two bar sections are cut (1 piece HC and 1 piece FL) in 2 040 s. The flow is then equal 2/2 040, which means that 2 units are processed in 2 040 seconds (sent to the stock P10out). The model of component separation for the P11Ain and P11Bin process input stocks is a reversal of the assembly kit completion process and is shown in Figure 7.

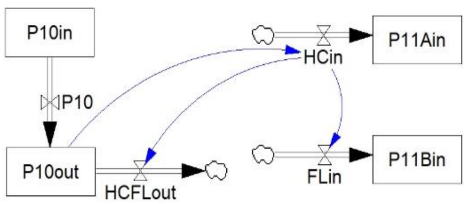

Figure 7. Model of manufacturing two types of components in one process (P10) and distribution of components to two different warehouses (P11Ain and P11Bin).

In the presented solution, the control flow is HCin (4):

$$\text{IF THEN ELSE(P10out>=8, 4, 0)} \quad (4)$$

According to the formula (4), if the P10out stock contains at least 8 components, then the HCin flow sends 4 HC components to the P11Ain stock. The FLin flow is equal to HCin, and the HCFLout flow is twice the HCin (i.e. the sum of HCin and FLin).

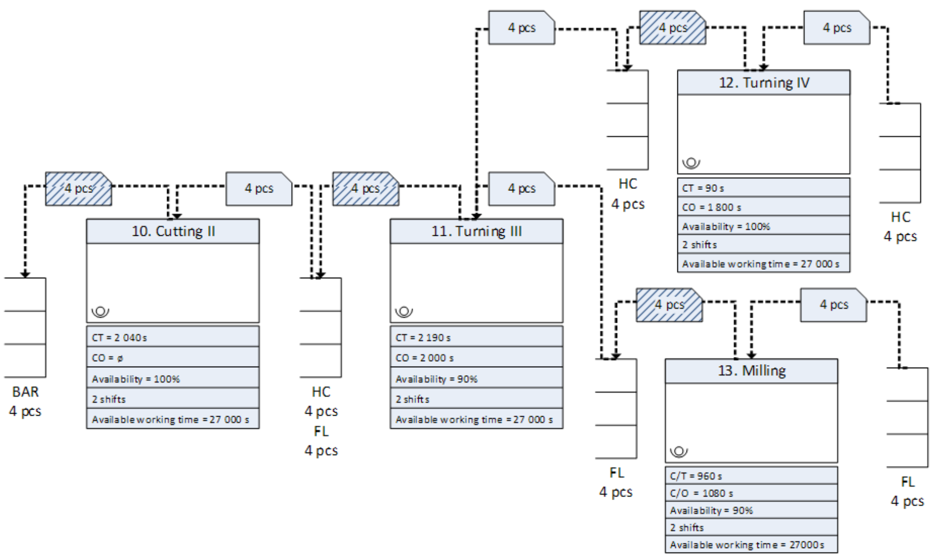

Figure 8. Fragment of the value stream map with process 10, in which two different components are produced.

The presented solution can be generalized for processing in one process n different components and the separation of these components into n different processes, provided that the contribution of each component to the whole is determined.

Figure 8 shows the corresponding VSMap fragment. The components produced in process 10 go to process 11, where they are processed in sequence (first one then the other) and then transferred to two different processes. When HC is ready it is transferred to process 12. Then when FL is ready it is transferred to process 13.

Problem 5. Two operators work on the same workstation performing the same process. This problem concerns workstation 17, on which manual assembly process is carried out. The employees at the assembly station work fully independently.

Solution 5-1. In the SD method, the basic parameter of a process (flow) is its efficiency (speed) expressed by the amount of material processed (passing through the process) per time unit. If the time unit is a second and the amount of material is expressed in pieces, then for processing 1 piece in 7 500 seconds the efficiency is 1/7 500. If the process is carried out manually by one employee, then adding a second employee to this process will double the efficiency (2 pieces will be processed in 7 500 seconds). The disadvantage of this solution is the inaccurate schedule of processed components. For example, in the simulation of a model constructed in such a way, after 3 750 seconds in the output stock of the process there will be 1 piece, while in the real-world process there will be two pieces "half-processed".

Solution 5-2. An alternative way of modeling two employees in one process is to create two workstations (each with one employee) working in parallel. This solution accurately reflects the situation in which two employees process two different components simultaneously (and independently of each other). This solution is much more complex than solution 5-1. In the case of modeling of parallel workstations in a part of the manufacturing line, it is necessary to involve the separation of components (e.g. as shown in problem 4) before the workstations working in parallel, then processing at parallel workstations, and then collecting processed components into one stock (similar to the solution in problem 3).

It is worth noting that in the case of processing even numbers of components, the schedule of transferred components will be the same for solutions 5-1 and 5-2. Because in the process under consideration (P17) the components are transferred in batches of 4 pieces, the model 5-1 was chosen as much easier to implement (Figure 9) (5). The analysed part of a VSMap is presented in Figure 10.

$$\text{IF THEN ELSE}(P17in>0,\ 2/7500,\ 0\ ) \tag{5}$$

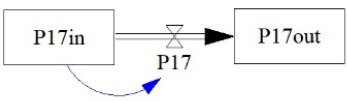

Figure 9. SDM of two operators performing the same process.

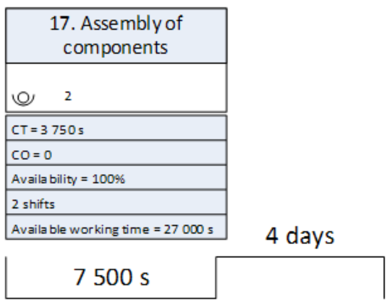

Figure 10. VSmap of two operators performing the same process.

Actually, from VSMap it is not clear how the work in Process 17 is organized. It is only presented that 2 operators are working, cycle time equals 3 750 seconds (what means that theoretically every 3 750 seconds one product leave the process) and that processing time of one product takes 7 500 seconds. However, it might be also organized like that two product leave the process after 7 500 s. In SDM this is precisely specified.

6. Conclusions

On the base of the presented work the following conclusions can be drawn:

- The VSMap is simplification of the material and information flow and SDM cannot be presented in a similar simple way.
- It is recommended to add in SDM the additional virtual stocks (in-stock with parts which will go into a process and out-stock with parts which will go out of a process) to be sure that discretization will be implemented. The maximum stocks size will depend on batch size.
- For information flow with the use of Kanban cards it is recommended to use "shadow variable" or simple arrow.
- For completing assembly kits an additional stock is recommended. While each component necessary to assemble a product will reach the stock, the kit is created and sent to the next process.
- If in a process two different components are manufactured with the same kind of material a separation process has to be implemented and two manufactured products have to be sent in two different stocks.
- When two or more operators are working in the process it is recommended to create two (or more) separate processes in SDM. In the analysed problem the work was realized by two operators in parallel. However, in other situation the operator could work in sequence (e.g. in one piece flow system). It should be clear from the beginning.

In the work different problems identified in the analysed manufacturing line were discussed. However, the authors are aware that also other problems which were not analysed here can be interesting for researchers who would like to create SDM.

In the future work a simulation model of the whole manufacturing line will be developed and simulated to analyse problems.

In the frame of this work the following problems were not discussed, e.g.:

- Workstations can work a different number of hours (shifts) during the day.
- An operator can work few hours on one workstation and few hours on another workstation.
- Workstations can have decreased availability.

The proposed solutions can be particularly useful in the case of modelling the company at the strategy and policy level, together with the need to detail the selected process, for example, to determine the impact of various operational scenarios of the process on the company performance. The approach can be considered as an alternative to the use SD-DES combination in such cases.

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