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3 **Analyzing the Effects of Lean Manufacturing**  
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5 **using a Value Stream Mapping based simulation generator**  
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## Analyzing the Effects of Lean Manufacturing using a Value Stream Mapping based simulation generator

### Abstract:

Value Stream Mapping (VSM) has become a popular implementation method for Lean Manufacturing in recent years. However, its limitations such as being time-consuming, its inability to detail dynamic behavior of production processes and to encompass their complexity, have spurred us to turn to simulation. This paper introduces two new elements to the Value Stream Mapping Method. First, it describes how the Value Stream Mapping Paradigm (VSMP) can be adapted for use in simulation, introducing specially designed VSM objects. Secondly, based on the VSMP and these objects, it presents a formal modeling method and its related database structure, that drives a generator which automatically yields a simulation model of the Value Stream Map. In this way, a model generator, using the set of objects and the model database, can generate simulation models of current and future VSM scenarios quickly and automatically. Additionally, algorithms for converting raw ERP data and information from a VSM drawing into tables of the structured database are developed. Finally, the formal modeling method is applied to a real company case. A Current State model of the manufacturing system and three scenarios of Future States are generated to see the effects of lean when transforming part of the system from push to pull.

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**Keywords**

Lean Manufacturing, Value Stream Mapping, Object-Oriented Simulation, Model

Generator

For Peer Review Only

## 1. Introduction

Womack, Jones, and Roos define 'Lean' as the elimination of *muda* (waste) in the book 'The Machine that Changed the World' (1990). Several cases are illustrated in the sequel 'Lean Thinking' (Womack and Jones 1996). In this book, crises of the companies in various industries (manufacturing tools, cars, airplanes, etc.) are tackled by applying the key principles of Lean Manufacturing (Womack and Jones 1996; Rother and Shook 1999). The surveyed companies are scattered around the world with different cultures (America, Germany, Japan) and sizes (a little company with 400 people to a big enterprise with 29 000 employees). The key principles are:

1. Define **Value** from the perspective of the customer,
2. Identify the **Value Streams**, and eliminate **Waste** from them
3. Create **Flow**,
4. Introduce **Pull**,
5. Strive to **Perfection**.

Despite the apparent simplicity of the Lean approach, its successful adoption by manufacturing companies has progressed slowly, both in the US as in Europe (Drickhammer, 2004; Engardio and Roberts 2004; Van Landeghem, 2005). One reason for this is the difficulty in accurately determining the impact of Lean transformations, especially when this requires changes in assets. Expensive factory layout redesigns, such as replacing a production line with large machines of mass production by a manufacturing cell with new, smaller machines is one example that has been reported (Rahn 2001; Sullivan et al. 2002). A change in the supply chain infrastructure is another one (Van Landeghem and Debuf 1997). In recent years, Value Stream Mapping (VSM) has emerged as the preferred way to implement lean, both inside factories and at the

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3 supply chain level linking those factories (Hines and Rich 1997; Hines, et al 1998a; id.  
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5 1998b; Hines and Taylor 2000; McDonald, et al 2000, id. 2002; Whitman et al. 2001;  
6  
7 Sullivan et al. 2002, etc.).  
8

9  
10 Value Stream Mapping (VSM) is a mapping paradigm used to describe the  
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12 configuration of value streams. It maps not only material flows but also information  
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14 flows that signal and control these material flows (Rother and Shook 1999). However,  
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16 since VSM is a paper and pencil method, it is limited in its modeling power. VSM is  
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18 also a static tool that cannot describe dynamic behavior and cannot handle neither  
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20 complexity nor uncertainty. Moreover, we might need at least a few months of a  
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22 continued monitoring to observe the effects of changes and improvements (Hines et al.  
23  
24 1998). On the other hand, we would like to preserve the VSM modeling language (i.e.  
25  
26 its standard icons), because of its ease of use and its widening dissemination within the  
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28 manufacturing community. Moreover, VSM also includes a step by step approach to  
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30 transform a current manufacturing state into a Lean future state, which is the basis of its  
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32 success in practice.  
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37 In the remainder of this paper, we first review some literature regarding enhanced  
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39 VSM tools. Since we use simulation as such a tool, studies concerning modular  
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41 simulation models and generators are also shortly reported on. Then, we describe the  
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43 formal Value Stream Mapping Paradigm (VSMP) in view of simulation and define the  
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45 framework and elements of an enhanced VSM approach, we call simulation-based VSM  
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47 (SimVSM) . The formal method is then applied to a real world company case. The  
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49 method's algorithms for converting raw ERP data and information of a VSM map into  
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51 tables of the structured database are briefly illustrated on the case. A Current State  
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53 model of the real manufacturing system case and three scenarios of VSM Future States  
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55 are generated to see the effects of lean manufacturing by transforming part of the system  
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3 from push to pull. Via the use of SimVSM, managers can see the impact of lean  
4 transformation before the actual implementation. This will increase confidence and  
5 hopefully enhance the rate of adoption of Lean Thinking in our manufacturing  
6 companies.  
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## 11 12 13 14 **2. Literature review**

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16 The limitations of traditional VSM have stimulated some researchers to develop  
17 ways to enhance it. Two types of enhanced tools are used in the literature: detailed  
18 mapping and simulation.  
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23 Sullivan et al. (2002) illustrate an equipment replacement decision problem within  
24 the context of lean manufacturing implementation and demonstrate how the seven VS  
25 detailed mapping tools (Hines et al., 1997, id. 1998, id. 2000) can be used to picture the  
26 current state of a production line and design a desired future state. Simulation, which  
27 creates consensus by its model-building interface, visualization of dynamic views and  
28 output analyzing capabilities, has also been applied as such an enhanced tool  
29 (McDonald et al. 2000, id. 2002). Two ways of simulation are described in literature:  
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- 38 • *Physical Simulations:* Whitman et al. (2001) present a physical simulation game  
39 where participants operate workstations along the assembly line in a mythical  
40 aircraft plant. Through a series of four scenarios (with different value stream maps),  
41 participants encounter problems with suppliers, service level, quality control and so  
42 on. As a result of participating in this game, people implement and learn about lean  
43 concepts such as cellular manufacturing, pull system, one-piece-flow, etc. We have  
44 been using this approach ourselves (Lian and Van Landeghem 2002), modifying an  
45 existing manufacturing game building Styrofoam trains, introduced by Van  
46 Landeghem and Dams (1995), to illustrate the VSM method.  
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- *Computer-Aided Simulations*: In (Van Landeghem and Debuf 1997; Van Landeghem 1998; McDonald et al. 2000; id. 2002; Rahn 2001) simulation is used to model manufacturing processes for a core product family and to validate the current supply chain map (or Current State map) as well as evaluating alternative scenarios. However, they failed to fulfill one thing: 'integration of VSM and simulation'. The results are long simulation modeling times (e.g. forty hours for a Future State model in McDonald, Van Aken and Rentes 2002) and models that are not reusable.

These shortcomings are typical for simulation studies (Valentin and Verbraeck 2001; id. 2002). One avenue of improvement has led to object-oriented modeling. Although Oldfather et al. (1966) developed the earliest simulation generator already in 1966, the concept of object-oriented modeling (or component-based modeling) used in conjunction with model generators arose in the mid-1990s due to the advent of supply chain integration, which increased the complexity of designing manufacturing systems and aggravated the drawbacks of traditional simulation studies.

Alfieri and Brandimarte (1997) indicated that the variety of tasks to be modeled in such systems calls for a modular approach which is characterized by reusable modules and stable interfaces to connect them, enabling the designer to experiment with different alternatives by simply assembling a set of predefined building blocks. Aytug and Dogan (1998) introduced a generalized framework for modeling a specific class of Kanban-controlled manufacturing systems, including a model generator based on this framework. They developed five major building blocks (work center module, production kanban monitoring module, withdrawal kanban monitoring module, material order module and customer order module) in simulation code, as well as a database and user interface. They illustrate the generator on a hypothetical manufacturing system.

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3 This generator is an enhanced version of Christenson and Dogan's (1995), where the  
4 system assumes that all parts must follow the same process routing. Son et al. (2003)  
5 describe a library of such formal, neutral models of simulation components for a  
6 discrete-event simulation of the flow of jobs through a job shop, based on a pre-  
7 provided schedule.  
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10 From our own research we found two additional benefits for using simulation models:  
11

- 12 • *Simulation as a Cost Saving Tool*: The use of a simulation model can help managers  
13 to see the effects before a big implementation: the impact of layout changes,  
14 resource reallocation, etc. on key performance indicators before and after lean  
15 transformation, and this without huge upfront investments (Van Landeghem and  
16 Debuf 1997, Rahn 2001).  
17
- 18 • *Simulation as a Training Tool*: Simulation has proven to be a powerful eye-opener  
19 (Van Landeghem and Debuf 1997; Van Landeghem 1998; McDonald et al. 2000; id.  
20 2002; Whitman et al. 2001. By combining simulation with the visual power of  
21 Value Stream Maps, we aim for faster adoption and less resistance to change from  
22 the workforce.  
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38 The integration of standard VSM icons and generated simulation models will enable  
39 non-expert users (e.g. companies) to develop simulation models after few sessions of  
40 practices. We achieved this integration in developing SimVSM.  
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### 48 **3. Value Stream Mapping Paradigm**

49 VSM provides a set of standard icons as a common language for describing  
50 manufacturing processes. The list of VSM icons provided by Rother and Shook (1999)  
51 fall into three categories: material flow, information flow and general icons. However,  
52 in order to be able to simulate these flows, we need to clearly establish the function of  
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3 each icon and determine their interrelationships. We call this enhanced meta-level view  
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5 of VSM the Value Stream Mapping Paradigm (VSMP). To describe it, we need to  
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7 define a new classification for VSM icons:  
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- 9 1. Basic Flow Unit Entities and Flows,
- 10 2. Physical Entities,
- 11 3. Buffer Entities,
- 12 4. Flow Control Entities,
- 13 5. Data Table and Measurement Entities.

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16 We can thus describe the VSMP as follows:  
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20 *Basic flow unit entities* (products, containers) are the objects that move through  
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22 *physical entities* (machines, manufacturing processes) and *buffer entities* (inventory,  
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#### 4. Simulation-based formal modelling method of Value Stream Maps (SimVSM)

The formal method we introduce is a discrete-event simulation-based method, which preserves the high-level modeling power of standard VSM, but compensates for the drawbacks of static VSM, and generates the model automatically without any of the limitations currently found in literature (such as single unit load, capacity limitations, non-stochastic times, or push environment only). The framework of our formal method is shown in Figure 1 and we explain its elements in what follows.

**Insert Figure 1 here**

##### 4.1. Atom formalism and manipulation

We have designed twelve specific atoms for SimVSM (atom ID 1-11, 18 in Table 1). The idea is that the functions, represented by the VSM icons, can be composed from these atoms and (possibly) some ED standard atoms (atom ID 12-17, 19 in Table 1). Then, simulation models for different VSM scenarios can be created automatically, through a generator that reads from a structured database which atoms to put in the model.

Atoms are object-oriented, self-contained modules describing the behavior of entities (e.g. machine, product, buffer, storage, etc.) within a manufacturing system. In connecting the atoms through links between the input/output channels of the atoms we provide dynamic flow information. Of course, these connections must adhere strictly to a set of rules, to guarantee that the model, once generated, can be run as a simulation and is correct. These rules are specific for each atom, as we will illustrate below.

It should be noted at this point that most simulation software engines are based on a 'push-through' flow paradigm to operate their models. Therefore, modeling PULL flow

requires quite some intricate atoms to achieve working models. In addition, a simulation model behaves as a close-coupled system, i.e. when the flow is blocked somewhere, all previous entities in the flow are also blocked. To avoid this, queues (buffers) have to be included at numerous places, typically before and after each process. For reasons of conciseness, we describe only the formalism and operating logic of the supermarket atom, which is part of the pull system. In a supermarket, a fixed amount of raw material, work in process, or finished product is kept as a buffer to absorb variability or shield off an incapable process. The amount is determined by the number of Kanbans, which also serve to control its replenishment.

#### 4.2. Supermarket atom description

A supermarket (Figure 2) is a buffer between two machines or processes, consisting of  $N$  trays, one for each product type. Each tray  $i$  ( $i=1,\dots,N$ ) is represented by one supermarket atom (VSMSUPR02 in table 1) and is filled initially with  $K_i$  kanbans, each containing  $M_i$  units. In a general situation, tray  $i$  contains  $k_i$  non-empty kanbans, with at most one of them partially emptied (containing  $r_i$  units), for a total of  $p_i$  product units. Thus, the number of products available in the supermarket tray  $i$  at any time adheres to

$$P_i = (k_i - 1) * M_i + r_i \quad \text{with} \quad 0 < r_i \leq M_i$$

As shown in Figure 2, we can divide the flows into two parts. The first part, demand delivery, is situated downstream of the supermarket atom. When a customer demand (outside trigger) arrives into the system, it requests the order quantity  $x_i$  from a supermarket atom through an order-process/withdraw atom (VSMOPRO01). The supermarket will then try to ship  $x_i$  parts. If there are enough kanbans in the supermarket atom ( $x_i \leq P_i$ ), the demand trigger will cause  $x_i$  products to proceed

1  
2  
3 downstream. A number of empty kanbans  $h$  will then be released upstream to replenish  
4  
5 the supermarket, with the remainder  $r'_i$  ready for the next request. We find  
6

$$7 \quad h = \lfloor (x_i - r_i) / M_i \rfloor + 1$$

$$8 \quad r'_i = (x_i - r_i) \bmod M_i, \text{ if } x_i \geq r_i \text{ and } r'_i = (r_i - x_i) \text{ else}$$

9  
10  
11 Otherwise, the unfilled portion of the demand will be put in a backlog queue until  
12  
13 enough products arrive from upstream.  
14

15  
16 The second part, kanban replenishment, is situated upstream of the supermarket  
17  
18 atom. The empty kanbans exiting from the supermarket are put in a staging queue,  
19  
20 controlled by a withdraw atom (VSMOPRO01). For each empty kanban, the withdraw  
21  
22 atom releases a production kanban to the production kanban wall (a queue itself). The  
23  
24 upstream manufacturing process atom (machine or work centre) then receives orders  
25  
26 from the kanban wall to produce its end-products to replenish the consumed parts of the  
27  
28 empty kanban. These products are attached to the waiting empty kanban in the withdraw  
29  
30 atom, until it is complete with its  $M_i$  units. The replenished full kanban is then sent back  
31  
32 to the supermarket to its tray  $i$ . Production thus replenishes one Kanban at the time.  
33  
34

35  
36 **Insert Figure 2 here**  
37  
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40

### 41 **4.3. Supermarket model relationships**

42  
43 The relationships of the supermarket atom with other atoms, which have to be  
44  
45 obeyed to obtain a valid model, are displayed in Figure 3 using the Entity-Relationship  
46  
47 formalism (Chen, 1976). In this figure a '1', 'M' or 'N' represent the cardinality of the  
48  
49 relationships: one-to-one, one-to-many, or many-to-many. A single or a double line  
50  
51 denotes an optional or a mandatory relationship and the naming of the relationships are  
52  
53 displayed inside diamond-shaped nodes. For each supermarket atom (one-to-one  
54  
55 relationship), there are three types of atoms that can be directly connected to it:  
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1  
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3 • The first output channel of the supermarket atom (VSMSUPR02) may (optionally)  
4 be connected to a kanban staging atom (VSMKSTA01): i.e. a supermarket atom may  
5 send empty kanbans to a kanban staging atom.  
6  
7

8  
9 • The second output channel of the supermarket atom (VSMSUPR02) must  
10 (mandatory) be connected to an order-processing/withdraw atom (VSMOPRO01): a  
11 supermarket atom must send products to a withdraw atom.  
12  
13

14  
15 • The only input channel of the supermarket atom (VSMSUPR02) may (optionally)  
16 be connected to an order-processing/withdraw atom (VSMOPRO01): a supermarket  
17 atom may receive full kanbans from an upstream withdraw atom.  
18  
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22 **Insert Figure 3 here**  
23

#### 24 **4.4. Database structure**

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26  
27 In the SimVSM method, a model generator written in the Enterprise Dynamics  
28 programming language reads the data from a database, taking the required atoms,  
29 connecting them and generating the simulation model through a wholly automatic  
30 process. This database describes the resources/entities, their layout and relationships  
31 within a manufacturing system and contains the information that is mentioned in a  
32 VSM. The database structure is displayed in Figure 4. Different data sets provided for  
33 the same structure will create different simulation models through the model generator.  
34  
35 When executing the generated simulation model, output measurements of products or  
36 orders such as lead-time, value-added time and value-added ratio are written into two  
37 output tables of the same database file. The database tables can be classified into four  
38 categories:  
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- 53 • *Meta-model database tables*: There are three tables belonging to this sort  
54 ('TypeInfo', 'ParameterDescriptors', 'AtomInfoPerType'). They contain data  
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1  
2  
3 respectively about the list of standard atoms, available for the generator, a list of  
4  
5 parameters with their description and a list indicating for each of those atoms which  
6  
7 parameters are needed. *The generator does not query them and the data within the*  
8  
9 *tables do not change from models to model.* Rather these tables contain the meta-  
10  
11 model on which the generator logic has been designed. Also, the user interface for  
12  
13 input of data uses this information to guide its query.  
14  
15

- 16 • *Generator database tables:* This type of database tables describes the resources  
17  
18 (atoms) of a manufacturing system, their layout location (X, Y, Z) and relationships  
19  
20 (connections). Via the information in the 'Connections' table, the generator then  
21  
22 constructs a 'Channels' table providing the identity of input and output related  
23  
24 entities for each specific entity. These tables are functional tables, which depict the  
25  
26 entities and contain the logic of the simulation model. The generator needs all these  
27  
28 tables to complete a simulation model (see data flow in Figure 4). *The data within*  
29  
30 *these tables changes from model to model.* There are four tables belonging to this  
31  
32 category: 'Atoms', 'AtomConnections', 'AtomChannels' and 'ParameterValues'  
33  
34 tables.  
35  
36
- 37 • *Input database tables:* These tables provide data values for the specific tables linked  
38  
39 to an atom (a specific ED construct). For instance, the atom 'VSMOPRO01' has a  
40  
41 corresponding bill of material table to allow assembly processes; the atom 'T098-  
42  
43 Table' which is an ED standard atom can be used as order data or setup time matrix  
44  
45 table.  
46  
47
- 48 • *Output database tables:* Two tables are filled with values when a measurement atom  
49  
50 'VSMDATA01' is used in the model. We can evaluate our system by these output  
51  
52 measurements (lead time, value-added time, service level, etc) as well as using the  
53  
54 standard output data supported by ED itself such as machine utilization, queue size,  
55  
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3 queuing time (WIP), etc. The definitions of some key measurements are given as  
4  
5 follows (Hopp and Spearman 1996; Rother and Shook 1999):  
6

- 7 • Work in Process (WIP): The inventory between the start and end points of a  
8 product routing. Inventory levels are converted to 'inventory time' in a VSM  
9 map according to Rother and Shook, 1999.  
10
- 11 • Lead-time (LT): The total time a customer must wait to receive a product after  
12 placing an order. When a scheduling and production system is running at or  
13 below capacity, lead-time and throughput time are the same. When demand  
14 exceeds the capacity of a system, there is additional waiting time before the start  
15 of scheduling and production, and lead-time exceeds throughput time.  
16
- 17 • Utilization (U): Fraction of time a workstation is not idle for lack of parts. If a  
18 workstation increases utilization without making other changes, average WIP  
19 and lead-time will increase in a highly nonlinear fashion.  
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32 **Insert Figure 4 here**  
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36

#### 37 **4.5. Model generator**

38 The model generator reads the data from a structured database, takes the required  
39 atoms (entity types/names), locates the position (layout of the entities), connects them  
40 (the relationships between the entities) and transforms the descriptions of a database  
41 into a simulation model automatically. The model generator is data-driven so that  
42 different data source under the same database structure will produce various simulation  
43 models with the only generator.  
44  
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50

51  
52 Simulation models are the final products of atoms, database and model generator. By  
53 changing the data in the database, we can yield a simulation model that corresponds to  
54 the new data set without any effort whatsoever (e.g. only point to the menu option or  
55  
56  
57  
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1  
2  
3 push the shortcut keys). In this way, different scenarios of VSM can be transformed into  
4  
5 simulation models in a short time and we can easily obtain feedback and improvements  
6  
7 to the system after analyzing and comparing the outputs of simulation models. This  
8  
9 allows for efficient analysis with the company people present, increasing their  
10  
11 involvement with the models. The generator thus allows us to follow closely the  
12  
13 standard VSM method of transforming the current state in one or more future states,  
14  
15 with different phases of execution. Now (for the first time) each phase of transformation  
16  
17 towards lean can be validated up front using specific generated simulation models.  
18  
19

#### 20 21 22 23 **4.6. SimVSM: the formal modeling procedure**

24  
25 We can summarize the modeling procedure of our formal method into five steps  
26  
27 (Figure 5):

##### 28 29 *Step 1: Determine the required raw input data through a VSM map*

30  
31 The aim of our VSM formal method is to enhance traditional VSM and compensate  
32  
33 the limitations of it. Therefore, the first step is to draw a VSM map of the system that  
34  
35 the manager would like to investigate. According to the VSM method both Current and  
36  
37 Future State VSM will be drawn. The static VSM provides basic information for the  
38  
39 model generator tables such as entities in the system, locations, simplified flows, setup  
40  
41 times and cycle times. To generate the links between atoms, we will need detailed flow  
42  
43 descriptions. It is important that a 'routing table' which describes the paths of all the  
44  
45 simulated products is supplied in this step. While the VSM map provides the 'table of  
46  
47 contents' of the model, and the basic topology of information and material flows, most  
48  
49 detailed data can be obtained directly from the company's ERP database, possibly after  
50  
51 some reformatting and filtering.  
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3 *Step 2: Data processing of the raw input data*  
4

5 Data processing is a step that transforms the raw input into the data format that can  
6 be used by the model generator. After the processing, four generator database tables  
7 ('Atoms', 'AtomConnections', 'AtomChannels' and 'ParameterValues') are produced.  
8 The conversion algorithm of the 'AtomConnections' table will be briefly described  
9 when applying it to the real company case.  
10  
11  
12  
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14

15  
16 *Step 3: Model generation*  
17

18 In this step, the model generator completes its duty (select, connect atoms, etc.)  
19

20  
21 *Step 4: Model execution*  
22

23 During model execution, the production control atom (VSMCUST02) will read in  
24 the customer order data provided by a table atom (T098-Table). With these two atoms,  
25 the release of orders can be simulated in two ways, push (MRP) or pull (Kanban). By  
26 simply ticking a 'Product' box to 'on' or 'off' the production control atom will release  
27 'products' or 'containers'. In the first case, the released products will push to  
28 downstream. In the second case, the containers request (pull) the order quantities from  
29 upstream and flow them through the system.  
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38  
39 *Step 5: Analyzing simulation results*  
40

41 Operational output measurements such as lead-time, value-added time, value-added  
42 ratio, machine utilization and queuing time are available after model execution for  
43 analysis.  
44  
45  
46

47 **Insert Figure 5 here**  
48  
49  
50

51  
52 **5. Illustrating the formal method using a real company case: Current State**  
53

54 We illustrate SimVSM through a real company case. The company, located in  
55 Belgium, is a major manufacturer of poultry and pig raising equipment, including  
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57  
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3 feeding, drinking, feed storage and feed transportation systems. The current  
4  
5 manufacturing system of their division 'Components Production' encounters a capacity  
6  
7 problem on a particular machine center (HYDRAP), leading to excessive lead-times that  
8  
9 jeopardize the due date performance of the final assembly line. The company wants to  
10  
11 introduce Lean into their operations, but hesitates because they do not clearly see the  
12  
13 consequences of this.  
14

15  
16 *Step 1: Determine the required raw input data through a VSM map*  
17

18  
19 The Current State VSM of the company is shown in Figure 6. This manufacturing  
20  
21 system consists of 31 main atoms (entities). Over the reference period to be simulated,  
22  
23 the production control center (atom ID 18) releases 975 production orders of 382  
24  
25 different components (i.e. product types) to the workstations. There are a total of 8  
26  
27 instances of workstations in the simulated system: (1) HYDRAP, (2) metal shear, (3)  
28  
29 laser-punching machine, (4) MULLER, (5) bending<2m, (6) bending<4m, (7)  
30  
31 Outsourcing, and (8) Others. Workstations 1, 2 and 4 are single-server workstations.  
32  
33 Workstation 3, 5 and 6 are stations with parallel machines (with respectively 3, 2, 2  
34  
35 machines). Workstation 7 is an outsourcing process whose cycle time is not considered  
36  
37 in the simulation and workstation 8 is a general workstation representing all 'other'  
38  
39 machines in the system. Before each workstation, there is an entity of staging inventory  
40  
41 (IDs 10-17) presenting the work-in-process. Some other entities are: order staging (20),  
42  
43 warehouse (9), measurements (21), Order / flow type / cycle time / setup time data  
44  
45 tables (19, 24, 25-31). The 975 production orders are also represented by atoms in the  
46  
47 system, but they are only produced during model execution, not in the stage of model  
48  
49 generation. The released orders are determined only by the data in the order data table  
50  
51 (ID 19).  
52  
53  
54  
55

56 **Insert Figure 6 here**  
57  
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3 In the production process, each component has a routing (flow type). A routing table  
4 indicates for each flow type (first column) in consecutive columns the sequential atoms  
5 to flow through, identified by their AtomID number. For example, a component with  
6 flow type 1 (routing data '1-16-8-15-1-17-7-9') will be manufactured through the  
7 system with the following sequence: 1) going to WIP inventory 16 and wait for the  
8 process of workstation 8, 2) processed by workstation 8, 3) going to WIP inventory 15  
9 and wait for the process of workstation 1 of HYDRAP, 4) processed by workstation 1,  
10 HYDRAP, 5) going to WIP inventory 17 and wait for outsourcing process, 6)  
11 outsourcing process 7, 7) going to the warehouse (atom ID 9). Most information at this  
12 stage can be entered manually, or can be generated automatically from an ERP database  
13 taking into account the AtomID numbers. In this case we identified a total of 54  
14 different flow types, covering the 382 product types.  
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28

### 29 *Step 2: Data processing of the raw input data*

30  
31 Two of the database tables, 'Atoms' and 'ParameterValues', can be readily filled in  
32 from the data in the VSM map:  
33  
34

- 35  
36 • 'Atoms' table: It contains information about the atoms needed for the simulation  
37 model. For instance, the HYDRAP machine in the factory can be represented by  
38 a manufacturing process atom called VSMPROC01 with TypeID 6 in the library.  
39 Its location (X, Y, Z) is (36,0,0) as derived from the drawing, using ED  
40 coordinates and its AtomID (1 in this case) will serve as reference for the  
41 subsequent links that will be generated in the connection tables.  
42  
43  
44  
45  
46  
47  
48
- 49 • 'ParameterValues' table: This table contains the parameter values. The required  
50 input functionality is programmed into the Access model database using VBA.  
51  
52  
53

54 The next step is to model the material and information flows as links or 'channels'  
55 inside the simulation model. Algorithms have been developed to convert raw data into  
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1  
2  
3 generator database data automatically. We shortly explain the algorithm to generate  
4  
5 atom 'connections' as follows.  
6

7  
8 First we generate a matrix, with as many columns and rows as there are atoms (31 in  
9  
10 our case). A programmed conversion algorithm reads raw data from the routing table,  
11  
12 converting the linear sequence of process steps into pairs of AtomIDs, for every two  
13  
14 consecutive steps. This information is stored in a FROM-TO matrix, but only if the  
15  
16 AtomIDs are present in the model. For example, the values of the first two consecutive  
17  
18 cells of flow type 11 are 10 and 2, representing a move from a storage to an operation  
19  
20 on the metal shear. The algorithm will therefore set the cell (10,2) to value 1. After all  
21  
22 combinations of two consecutive cells are read, the remaining cells are set to 0. The  
23  
24 algorithm then counts the number of input/output connections and generates  
25  
26 input/output channels ids (ic/oc) for each atom. These are written into the  
27  
28 'AtomConnections' table automatically. These programmed algorithms are written in  
29  
30 VBA inside the Access database.  
31  
32

#### 33 34 *Step 3&4: Model generation and execution*

35  
36 Through the model generator, a simulation model is generated automatically in terms  
37  
38 of the data set from the four generator database tables. Figure 7 is a screen shot of the  
39  
40 generated company model (Current State). Note the arcs, denoting the links or channels  
41  
42 that 'wire' the model, that were generated. They can be made invisible to enhance visual  
43  
44 inspection of the model.  
45  
46

47  
48 **Insert Figure 7 here**

#### 49 50 *Step 5: Simulation results - Current State*

51  
52 We summarize the simulation output in Table 2 and 3. As we can also see in the  
53  
54 histogram 'Utilization' within the model of Figure 7, the utilization of HYDRAP is  
55  
56 high. Its average utilization is 55.3 % and average waiting time of each order is 347.22  
57  
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3 minutes before it can be processed by HYDRAP. The average order lead-time is 0.987  
4  
5 days and the value-added time is 0.15 days. There are 300 orders that are fulfilled  
6  
7 beyond their due date. This is 31% of the 975 production orders that were released  
8  
9 during three months. This type of diagnostic information is clearly not available in the  
10  
11 static VSM.  
12

13  
14 **Insert Table 2-3 here**

15  
16 *Future State mapping of the case*

17  
18 There are seven guidelines to introduce lean thinking into a value stream, according  
19  
20 to Rother and Shook (1999). Applying them to our case study, we introduced the  
21  
22 following changes to our model:  
23

- 24  
25 • install supermarkets before HYDRAP, and control the upstream replenishment  
26  
27 processes through a pull system (using Kanbans) for the high-volume products (ten  
28  
29 types). This required introducing new atoms and ‘rewiring’ the information flow.  
30  
31 The material flow basically remains unchanged. The number of atoms increased to  
32  
33 84 in the Future State models, from 31 in the Current State  
34  
35 • synchronize the takt time of production on HYDRAP (the bottleneck) to match the  
36  
37 pace of customer demand by changing the release rate of the production orders.  
38  
39

40  
41 Because transformation to Lean is best done in small steps we decided to limit the  
42  
43 Kanban-controlled products to ten types only. Our Future State thus forms a hybrid  
44  
45 push-pull system, which is fairly complex to grasp without simulation. The Future State  
46  
47 value stream map of the three scenarios is shown in Figure 8. We explain the scenarios  
48  
49 below.  
50

51  
52 **Insert Figure 8 here**

- 53  
54 • Current State: 975 push orders.  
55  
56  
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- Scenario 1: Install supermarkets for ten product types before HYDRAP machine. This leads to 946 push orders and 29 pull orders, being processed together in a FIFO sequence by the HYDRAP.
- Scenario 2: same as scenario 1, but we now give priority to the kanbans released from the supermarkets in each of the queues.
- Scenario 3: Same as scenario 2, but now push orders are released according to the takt time which is defined as the available production time divided by the rate of customer demand (Womack and Jones 1996; Rother and Shook 1999). For example, if the customer demand is 160 units per day and the production capacity is two shifts (16 hours), the production control will only release production orders worth (approximately) ten units per hour. Pull orders of course will by definition follow this takt time already.

*Summary of simulation results: Current States v.s. Future States*

In comparing the Future State simulations with the previous Current State, we can measure the impact of the switch to lean on order lead-times, queuing times and machine. The simulation results are shown in Tables 4-6. The queuing times before machines are reduced significantly, especially for the high utilization machines like laser-punch and HYDRAP (Table 4). Tables 5 and 6 are the results of 29 orders from the ten chosen products in the Current State and three Future States. Average lead-times are decreased nearly by half from current to scenario 3 of the Future State and the average value-added ratios are raised about 15% (Tables 5-6). The effects of lean are clearly shown by applying SimVSM to this real case study. It is worth stressing at this point that the concept of prioritizing Kanban orders was not even contemplated by the company involved, let alone that the beneficial effects were known in advance. It

1  
2  
3 illustrates the kind of additional information that can only be obtained from a simulation  
4  
5 model. The case study also showed us:

- 6  
7 • the validity of the generated models, even for (relatively) large-scale models  
8 based on real-world data
- 9  
10 • the correctness of our choice to use the VSM paradigm as basis for our modeling  
11 method, achieving a good balance between the complexity of the models, and  
12 ease of use in the modeling itself
- 13  
14 • the value of using simulation in the VSM approach in convincing companies to  
15 adopt Lean as a guiding principle, clearing away much of the ‘uncertainties’ that  
16 otherwise would hinder this adoption or block it altogether

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**Insert Table 4-6 here**

## 6. Conclusions and further research

This article introduces two new elements to the Value Stream Mapping method of Rother and Shook. First of all, a formal Value Stream Mapping Paradigm for the purpose of simulation is defined, and its specifically designed meta-level building blocks are presented. Second, the integration of simulation with Value Stream Mapping into the SimVSM method has been developed, the appropriate tools built and tested on a real life case. The framework and elements of the formal method: atoms, database structure and model generator, are described and illustrated. Finally, the SimVSM method is illustrated on a real case from a Belgian company. A Current State model of the real manufacturing system and three scenarios of Future States are generated to see the effects of lean by transforming part of the system from push to pull. Because of the generator approach, making new scenarios, simulating them and discussing the results with the company people can be done in limited time (typically one afternoon, the same

1  
2  
3 for modelling and discussion of Current State), which we believe is a considerable  
4  
5 improvement in operational modelling. The fact that our method preserves the power  
6  
7 and conciseness of the VSMP enables our method to be used in practice with limited  
8  
9 training or effort.  
10

11  
12 Through our simulation-based value stream mapping, static VSM maps of Current or  
13  
14 Future States are transformed automatically into dynamic simulation models. The  
15  
16 enhanced information, obtained from the simulation results, can provide feedback to  
17  
18 guide continuous improvements and hopefully will lead more enterprises to a lean  
19  
20 status.  
21

22  
23 Some focal points of future research will be:

24  
25 1. Integrate VSM icons into Office templates (i.e. VISIO). After drawing a value  
26  
27 stream map in VISIO, most database tables could then be filled automatically.  
28

29  
30 2. Study the impact of data aggregation (SKU's into families, detailed routings into  
31  
32 manufacturing cells, etc.) on the results from the VSMP.  
33

34  
35 3. Focus on the generator technical structure, and broaden its appeal to different  
36  
37 paradigms (other than VSM), also related with manufacturing.  
38

39  
40 4. Adapt the generator to simulate business processes, using a slightly adapted form  
41  
42 of the VSMP.  
43  
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Table 1. Value Stream Mapping Paradigm and its VSM Atoms

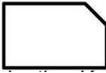
VSM Class	Functionality Description	VSM Icon	VSM Atoms (ID)
1. Basic Flow Unit Entities and Flows	The unit objects that pass through or detain in other categories of entities. The movements of these unit objects form the flows of the system.	<i>(A) Basic Flow Units</i>	
		Product 	▪ T050-a-Product (19)
		Kanban 	▪ T059-a-Container (16)
		<i>(B) Flows</i>	
		Information 	▪ Atom mechanism ▪ T059-a-Container (16)
		Push 	Natural flow movement
		Pull 	▪ VSMOPRO01 (8) ▪ T059-a-Container (16)
2. Physical Entities	Tangible objects in the system, one-to-one (or many-to-one) with real situations.	Process box 	▪ VSMPROC01 (6) ▪ VSMMPRO01 (18)
		Outside source 	▪ VSMSUPP01 (5) ▪ VSMCUST02 (10)
		Supermarket 	▪ VSMSUPR02 (1)
		Safety Stock 	▪ VSMSTOR01 (2)
3. Buffer Entities	Objects that can be only logical existence or the actual ones in the system.	Buffer 	▪ VSMSTAG01 (4) ▪ VSMPLL01 (7)
		Kanban Wall 	▪ VSMKSTA01 (3)
		Kanban Post 	▪ VSMKWAL01 (9)
4. Flow Control Entities	Objects that are needed to control the simulation flows such as push, pull, unpack the products from a container (box), flow separation and flow termination, etc.	Production control 	▪ VSMCUST02 (10) ▪ T098-Table (15) ▪ VSMOPRO01 (8)
		Others	▪ T007-d-Unpack (12) ▪ T009-b-Splitter (17) ▪ T054-a-Sink (14)
5. Data Table and Measurement	Objects that are needed to provide data for simulation execution and extract or monitor data from that due to ED requirement.	Data Box 	▪ Atom Parameters ▪ T098-Table (15)
		Timeline 	▪ VSMDATA01 (11) ▪ T090-b-Monitor (13) ▪ ED Report

Table 2. Machine utilization: Current State \*

Work Station	Shear	Laser-Punch	MULLER	Bending<2m	Bending<4m	HYDRAP
Utilization (%)	2.1	53.2	19.1	55.3	10.6	55.3
Waiting Time (min)	8.41	265.25	159.04	122.85	8.77	347.22

\* Based on 2 shifts

Table 3. Lean Indicators: Current State

(In Days)	Lead-Time	Value-Added Time
Average	0.9873	0.1504
Max	9.0832	1.8461
Min	0.0049	0.0014

Table 4. Waiting time (minutes): Simulation results\*

Work Station	Shear	Laser-Punch	MULLER	Bending<2m	Bending<4m	HYDRAP
Current State	8.41	265.25	159.04	122.85	8.77	347.22
Scenario 1	8.41	255.65	159.34	139.14	10.22	339.96
Scenario 2	8.41	251.93	159.34	122.80	9.81	331.01
Scenario 3	0.00	63.57	82.70	112.95	12.34	291.87

\*Based on 2 shifts

Table 5. Lean Indicators (minutes): Simulation Results

Indicators	Average Lead-Time	Average Value-Added Ratio (%)
Current State	1810	43.80
Scenario 1	1479	48.40
Scenario 2	1116	51.95
Scenario 3	973	58.49

Table 6. Lead-Time Reduction (%): Simulation Results

From / To	Scenario 1	Scenario 2	Scenario 3
Current State	18.30	38.36	48.23
Scenario 1		24.56	36.64
Scenario 2			16.02

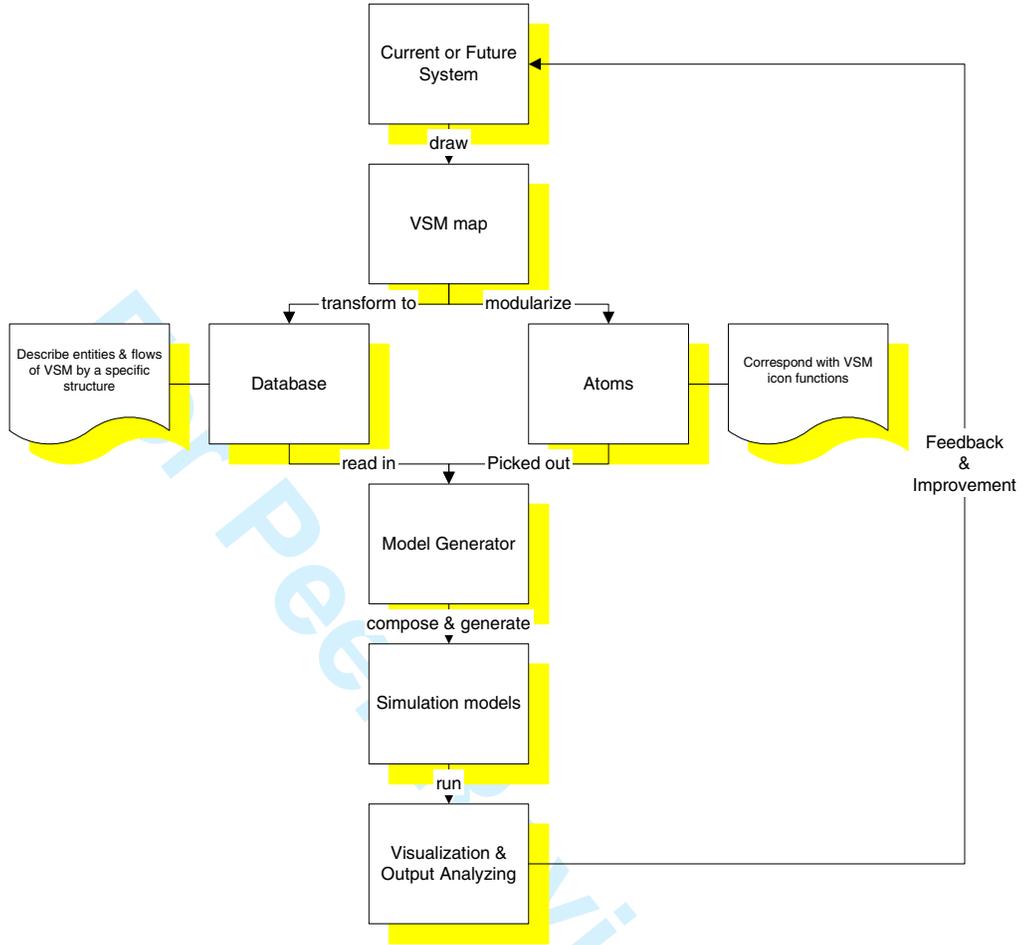


Figure 1. Formal method framework

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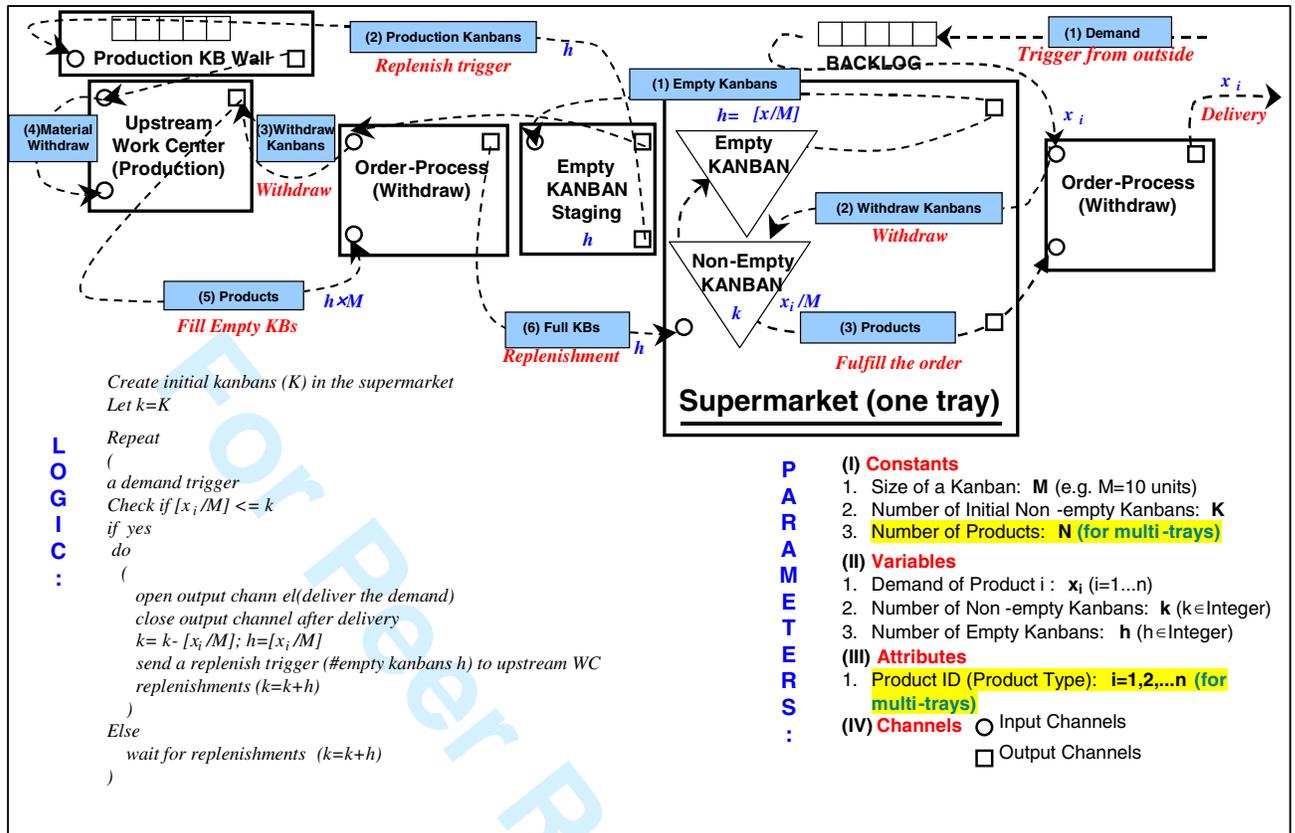


Figure 2. Supermarket (VSMSUPR02) atom formalism

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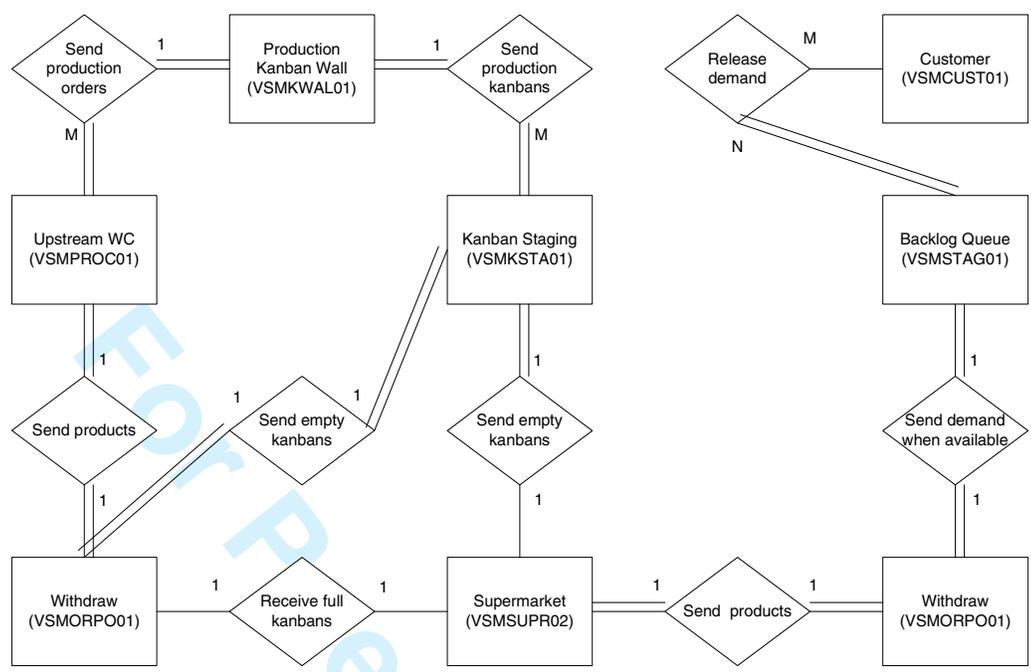


Figure 3. A simple ER-diagram of atoms related to supermarket atom

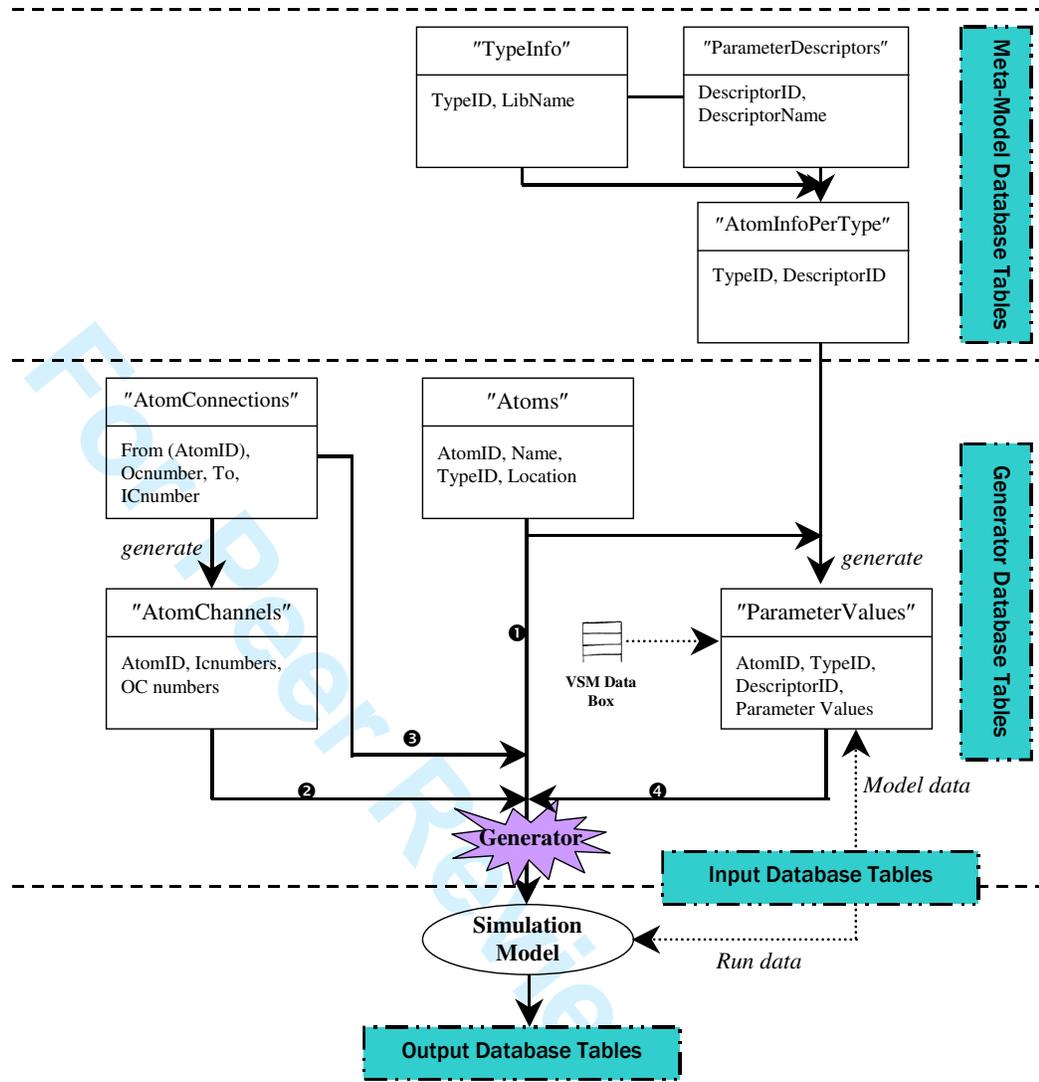


Figure 4. Database structure

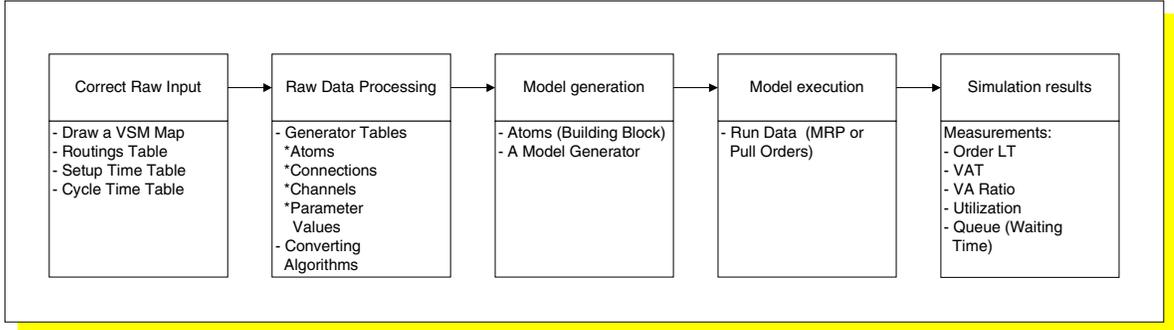


Figure 5. Modeling procedure of the simulation-based VSM formal method

Peer Review Only

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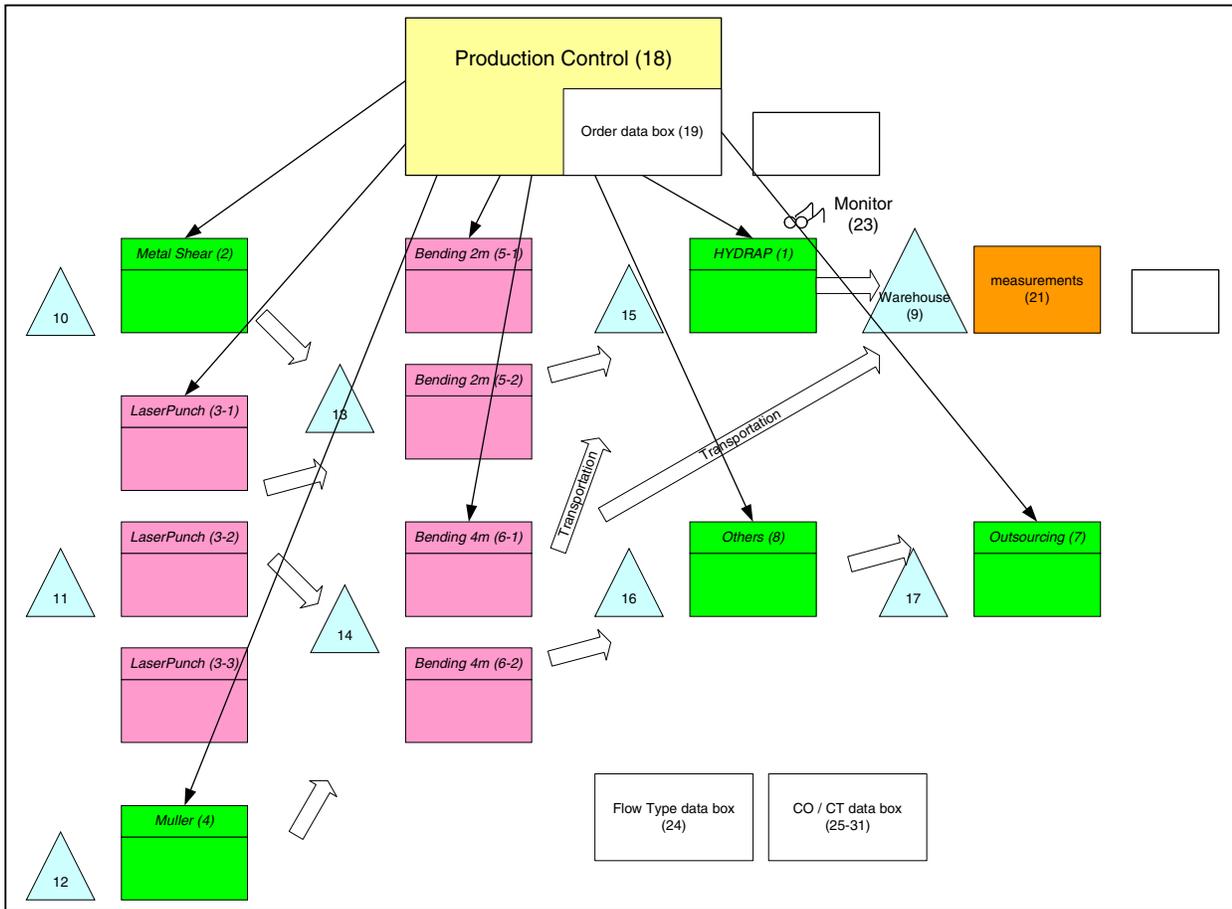


Figure 6. Current State of the Value Stream Map of the company case (31 entities)

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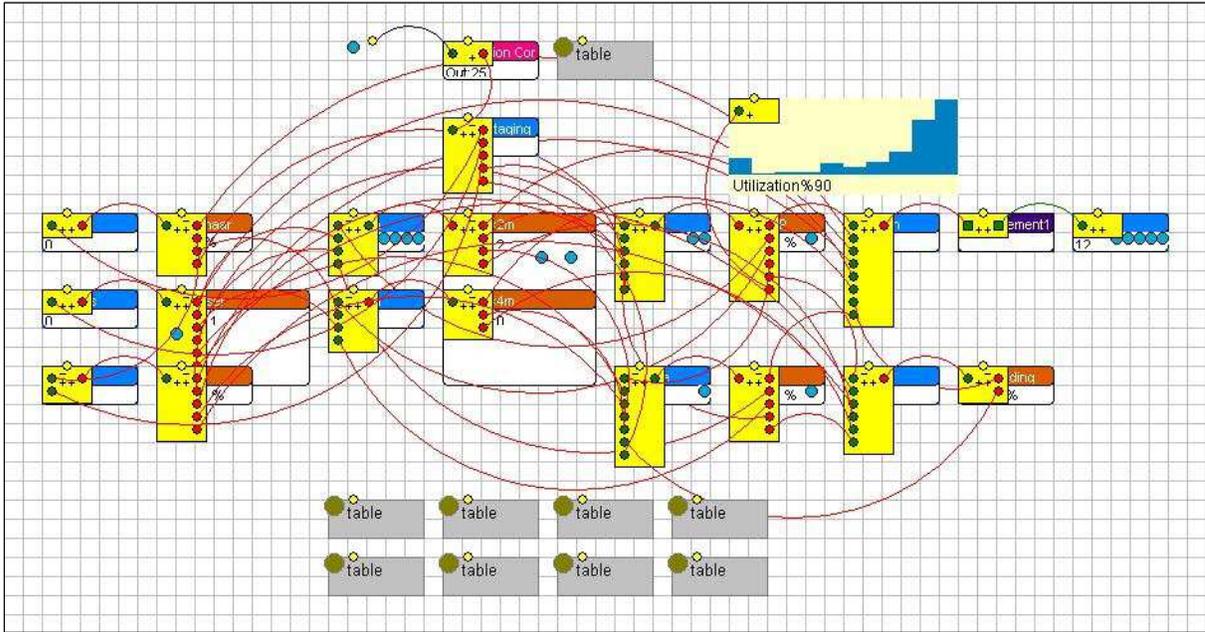


Figure 7. . A screenshot of the running generated simulation model inside ED

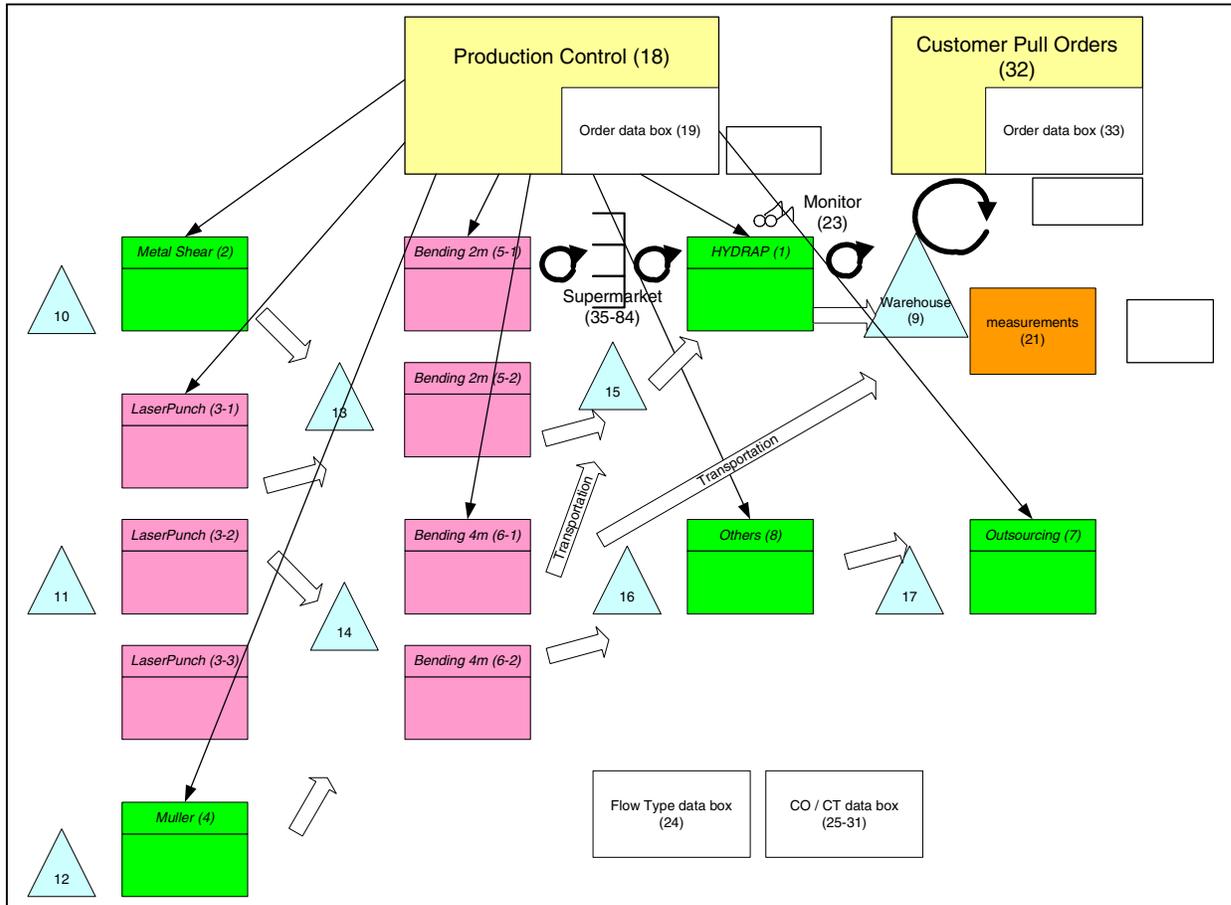


Figure 8. Future State of the Value Stream Map of the company case (84 entities)