# Ontwerp van een raamwerk voor een Lean Manufacturing Execution System

# Design of a Lean Manufacturing Execution System Framework

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# List of Acronyms

## 123

| | |
|---|---|
| 5S | workplace organization |

## A

| | |
|---|---|
| ADO | ActiveX Data Objects |
| aVSM | automated Value Stream Mapping |

## B

| | |
|---|---|
| B2M | Business to Manufacturing |
| B2MML | Business to Manufacturing Markup Language |
| BI | Business Intelligence |
| BPM | Business Process Management |

## C

| | |
|---|---|
| CAD/CAM | Computer-Aided Design and Computer-Aided Manufacturing |
| CI | Continuous Improvement |
| CIM | Computer Integrated Manufacturing |
| CONWIP | Constant Work In Process |
| C/O | Change-over Time |
| CRM | Customer Relationship Management |
| C/T | Cycle Time |

## D

| | |
|---|---|
| DCS | Distributed Control System |
| DES | Discrete Event Simulation |
| DMAIC | Define-Measure-Analyze-Improve-Control |

## E

| | |
|---|---|
| EAI | Enterprise Application Integration |
| eCONWIP | electronic CONWIP |
| EDD | Earliest Due Date |
| eKanban | electronic Kanban |
| EPE | Every Part Every |
| ER | Entity Relationship |
| ERP | Enterprise Resource Planning |
| ESB | Enterprise Services Bus |
| eVSM | electronic Value Stream Mapping |

## F

| | |
|---|---|
| FCFS | First Come - First Served |
| FIFO | First In - First Out |

## G

| | |
|---|---|
| GUI | Graphical User Interface |

## H

| | |
|---|---|
| HMS | Holonic Manufacturing Systems |

## I

| | |
|---|---|
| IT | Information Technology |

| | |
|---|---|
| ISA | International Society of Automation |
| ISA 95 | the $95^{th}$ standard of the International Society of Automation |

## J

| | |
|---|---|
| JIT | Just In Time |

## K

| | |
|---|---|
| KPI | Key Performance Indicator |

## L

| | |
|---|---|
| LES | Logistics Execution System |
| LIMS | Laboratory Information Management System |

## M

| | |
|---|---|
| MAS | Multi-Agent Systems |
| MDM | Master Data Management |
| MES | Manufacturing Execution System |
| MESA | Manufacturing Enterprise Solutions Association |
| MI | Manufacturing Intelligence |
| mMDM | manufacturing Master Data Management |
| MMS | Maintenance Management System |
| MOM | Manufacturing Operations Management |
| MOMS | Manufacturing Operations Management Software |
| MRP II | Manufacturing Resource Planning |
| MSB | Manufacturing Services Bus |
| MTO | Make To Order |

## O

| | |
|---|---|
| ODBC | Open Database Connectivity |
| ODS | Operations Data Store |

| | |
|---|---|
| OEE | Overall Equipment Effectiveness |
| OPC | OLE for Process Control |
| OPEX | Operational Excellence |

## P

| | |
|---|---|
| P2E | Plant-to-Enterprise |
| P2P | Point-to-Point |
| PCS | Production/Process Control System |
| PDCA | Plan-Do-Check-Act |
| PET | Poly Ethyleen Tereftalaat |
| PLC | Programmable Logic Controller |
| PLM | Product Lifecycle Management |
| PLT | Product Lead Time |
| POLCA | Paired-cell Overlapping Loops of Cards with Authorization |
| PPC | Production Planning and Control |
| P/T | Process Time |

## R

| | |
|---|---|
| RFID | Radio Frequency Identification |
| ROI | Return On Investment |
| RVA | Ratio Value Added |

## S

| | |
|---|---|
| SCADA | Supervisory Control and Data Acquisition |
| SCM | Supply Chain Management |
| SKU | Stock Keeping Unit |
| SME | Small and Medium-sized Enterprises |
| SMED | Single Minute Exchange of Dies |
| SOA | Service Oriented Architecture |
| SOP | Standard Operating Procedures |
| SOT | Shortest Operation Time |
| SQL | Structured Query Language |

## T

| | |
|---|---|
| TCO | Total Cost of Ownership |
| TCT | Total Completion Time |
| ToC | Theory of Constraints |
| TPM | Total Productive Maintenance |
| TQM | Total Quality Management |
| TRI | Total Required Inventory |

## U

| | |
|---|---|
| URS | User Requirements Specification |
| U/T | Uptime |

## V

| | |
|---|---|
| VNM | Value Network Mapping |
| VSM | Value Stream Mapping |

## W

| | |
|---|---|
| W/C | Work content |
| WIP | Work In Process |
| WMS | Warehouse Management System |

## X

| | |
|---|---|
| XML | eXtensible Markup Language |

# Nederlandse samenvatting –Summary in Dutch–

Om competitief te blijven, worden productie omgevingen geconfronteerd met een constante druk om steeds beter en sneller te produceren. Het is een voortdurende strijd om onnodige productiekosten te elimineren; productie-, proces- en bedrijfsprestaties te verbeteren; cyclus tijden te reduceren; kwaliteit te bewaken; enz. Om deze doelstellingen te ondersteunen, wordt gestreefd naar een gepaste automatiseringsgraad. Manufacturing Operations Management (MOM) activiteiten coördineren personeel, machines en materialen bij het verwerkingsproces van grondstoffen tot eindproducten. Een Manufacturing Execution System (MES) kan zorgen voor een efficiënt beheer van deze operaties. Het hoofddoel is het verzorgen voor een digitale informatie uitwisseling in plaats van communicatie op papier of via spreadsheets. Tegenwoordig is bij veel bedrijven de software ondersteuning niet meer weg te denken, door wettelijke bepalingen (vb. het traceren van producten binnen de voedings- en farmaceutische industrie), een hoge product variatie, enz.

Bedrijfsstrategieën en -eisen worden continu bijgesteld om de recentste klanteisen en industriële trends te kunnen volgen. Productie omgevingen zijn dynamisch; waarbij producten en productieprocessen constant worden bijgestuurd. De hedendaagse, veeleisende bedrijfscultuur stimuleert de toepassing van continue verbeter initiatieven; zoals Lean en Six Sigma; bij het streven naar zakelijke en operationele uitmuntendheid. Een MES herbergt een schat aan informatie die aangewend kan worden om verliezen te identificeren en te elimineren. Het automatiseren van informatiestromen in de MOM laag, kan opportuniteiten blootleggen voor verdere optimalisaties door continue verbeter initiatieven. De voordelen kunnen verder reiken dan enkel het oorspronkelijke doel van het louter automatiseren van de informatiestromen. Helaas slagen veel bedrijven er niet in om het volledige potentieel van de beschikbare data te benutten. De literatuur vermeldt twee problemen:

1. **Het gebrek aan bruikbare analytische omgevingen bovenop de realtime data collectie:** Productiecontrole systemen benadrukken operationele aspecten en verwaarlozen te vaak de beschikbare operationele data. De analyse- en rapporteringsmogelijkheden van MES zijn niet altijd conform de eisen van het bedrijf. Het ingeven van bedrijfsgegevens in losstaande Lean software is tijdsintensief en foutgevoelig. Het zelf ontwikkelen van software om verliezen te lokaliseren is daarentegen een dure aangelegenheid.

2. **Het gebruiksgemak blijft een hindernis voor de toepassing van Lean software op de productievloer:** Softwaresystemen missen veelal de nodige flexibiliteit om frequente wijzigingen te volgen en geraken zo gemakkelijk verouderd. De opkomst

van nieuwe technologieën (vb. Service Oriented Architecture (SOA)) maakt het steeds meer mogelijk om te voldoen aan de decentrale informatienoden van Lean specialisten. Voorlopig rapporteert een AMR onderzoek nog steeds een beperkte toepassing van Lean IT.

Volgens de voorgestelde combinatie van Lean tools en technieken (MOM optimalisatie) en MES productie controle (MOM digitalisering), kan een bedrijfsaanpak gradueel onderverdeeld worden in drie categorieën: (1) Geen afstemming; (2) Lean MES afstemming; en (3) Lean MES integratie. Geen afstemming betekent dat er geen interactie is tussen beide. Lean specialisten verzamelen hun informatie manueel en vermijden het gebruik van IT, zelfs als digitale informatie beschikbaar is. MES focust op push controle principes en machine efficiëntie (vb. Overall Equipment Effectiveness (OEE)) en verwaarloost waardestroom aspecten zoals doorlooptijdverkorting, load levelling, opsporen en elimineren van verliezen, enz. Uiteindelijk leidt de losstaande toepassing van MES en Lean tot een discrepantie tussen de verbeteringen en de controlesystemen op de productievloer. Als gevolg bereikt geen van beide strategieën de beoogde resultaten. Een Lean MES afstemming zoekt mogelijkheden om beide strategieën effectief te combineren binnen een specifieke situatie en zo elkaar te laten ondersteunen. Wanneer deze afstemming automatisch en regelmatig onderhouden wordt, is sprake van een Lean MES integratie.

Het doctoraatsonderzoek stelt een Lean MES raamwerk voor dat de vereisten structureert om een Lean MES integratie te initiëren en te onderhouden. In dit raamwerk krijgt MES een dubbele taak: het integreren van Lean ondersteuning en het implementeren van Lean aanpassingen. De $95^{ste}$ standaard van de International Society of Automation (ISA) is een industriële standaard voor de integratie van bedrijfs- en productiesystemen. Daarom wordt ISA 95 vooropgesteld als een gemeenschappelijk informatiemodel voor MES en Lean. De verschillende onderdelen van de Lean MES worden toegepast op de Manufacturing 2.0 architectuur.

Een geautomatiseerde Value Stream Mapping (aVSM) methodologie illustreert een mogelijke toepassing van het Lean MES raamwerk. Omdat huidige MES implementaties weinig tot geen aandacht besteden aan flow efficiëntie, wordt VSM in detail uitgewerkt. Het is niet de bedoeling om een tool te creëren die automatisch de volledige VSM analyse kan uitvoeren. De menselijke inbreng zal altijd de drijvende kracht zijn van de VSM oefening. Maar door gebruik te maken van de historische operationele data, kan MES de nodige ondersteuning bieden tijdens de analyse. Een elektronische VSM template kan gegenereerd worden als start of ter validatie van de manuele oefening. Bijkomende tools kunnen helpen om verliezen te identificeren en een nieuwe toestand (future state) voor te stellen. Sectie 3.3 bespreekt de toepassing van ISA 95 om de Lean MES activiteiten te standaardiseren. Standaard voorstellingen van productfamilies; VSM iconen; typische VSM gegevens en berekeningen; en pull productiecontrole principes staan vermeld. Een aantal standaard algoritmes (vb. identificeren van productfamilies, current state mapping, lijn balancering, configuratie van kanban loops, enz.) maken gebruik van deze Lean voorstellingen om de beschikbare operationele data te analyseren. De vereisten om het raamwerk in de toekomst uit te breiden met andere Lean tools en technieken worden opgelijst. Om de verbeteringen te waarborgen - en zo de Lean MES integratie te onderhouden - beschrijft sectie 3.4 een ISA 95 gebaseerde change management aanpak. De aanpak toont hoe de productiecontrole van MES - als Lean IT systeem - geïmplementeerd (greenfield) of aangepast (brownfield) kan worden om typische Lean operationele aanpassingen te volgen. Een aantal standaard change work flows - die noodzakelijk zijn binnen de aVSM analyse - worden voorgesteld: introductie van een nieuw product, rapportering op maat en omschakeling naar pull flow. Historische data ondersteunen deze standaard aanpassingen. Deze ondersteuning reduceert de omsteltijd en mogelijke fouten of inconsistenties binnen MES. Dit heeft dan weer een positieve invloed op de Total Cost of Ownership (TCO) van het systeem. Het is wel een uitdaging om het dynamische karakter van MES te koppelen aan de statische natuur van Lean. Een voorstel wordt geformuleerd om deze transities in de tijd praktisch te realiseren.

Een gebrek aan reële test omgevingen voor MES concepten bemoeilijkt de validatie ervan. Als een eerste stap, wordt de haalbaarheid van het Lean MES raamwerk gecontroleerd. Is het in staat om de vooropgestelde taken te vervullen? Resulteert de beschreven input (match Lean met ISA 95 terminologie) in de beloofde output (standaard Lean ondersteuning)? Eerst wordt een simulatie voorbeeld uitgewerkt om de voorgestelde aVSM methodologie te verifiëren. Hoe accuraat het simulatiemodel ook is, het blijft slechts een benadering van de realiteit en het kan de complexe dynamiek van een productie omgeving niet volledig nabootsen. Om het Lean MES raamwerk ten volle te valideren, moet gecontroleerd worden of het raamwerk een bedrijf kan ondersteunen bij het ontdekken van mogelijkheden, het sturen van het proces, het bereiken van de doelstellingen en het vasthouden van de verbeteringen van de continue verbeter initiatieven. Twee bedrijven werden geselecteerd voor een offline analyse. Elke case illustreert een specifieke toepassing van het raamwerk. Case A behandelt een groot productiebedrijf van frisdranken. De batch processen zijn sterk geautomatiseerd en de productie controle geniet al heel wat software ondersteuning. Case B analyseert de situatie van een klein meubelbedrijf. De productieprocessen hebben een sterk manueel karakter en de software ondersteuning van het discreet proces is beperkt. In beide gevallen wordt aangetoond hoe het raamwerk gebruikt kan worden om standaard Lean functionaliteit te integreren met historische gegevens. Door de data te transformeren naar de ISA 95 modellen, kan dezelfde tool gebruikt worden om beide situaties te analyseren. De resultaten van beide gevallen illustreren dat aVSM in staat is om waardevolle informatie te extraheren uit de beschikbare operationele data en dit ter beschikking te stellen van de analyse. Dit is echter onvoldoende om over een validatie van het raamwerk te spreken. Vanuit de opgedane ervaring worden de vereisten voor een toekomstige validatie beschreven. Daarnaast wordt een benchmark platform voorgesteld dat de evaluatie van MES onderzoeksresultaten moet mogelijk maken.

Binnen het voorgesteld Lean MES raamwerk, is aVSM slechts de eerste stap in de richting van een standaard analytische omgeving bovenop realtime data collectie. Door de ondersteuning voor continue verbetering uit te breiden, kan een volledig gamma van tools ontwikkeld worden. Een korte beschrijving voor de integratie van TPM is voorzien. Andere mogelijke uitbreidingen zijn TQM, six sigma, intelligentie ter ondersteuning van Lean toolselectie en -planning, etc. Elk systeem dat de standaard taal (ISA 95) spreekt en begrijpt, kan dan ingeplugd worden in deze voorgedefinieerde toolbox om MOM optimalisaties op te zoeken. Er is een commercieel MES pakket beschikbaar dat ISA 95 hanteert als onderliggend data model. De mogelijkheid moet onderzocht worden of daarin een piloot applicatie kan ontwikkeld worden voor aVSM. Dat zou een validatie op grotere schaal mogelijk maken van de voorgestelde aVSM methodologie in het bijzonder en het Lean MES raamwerk in het algemeen.

# English summary

Production environments face constant pressure to produce better and faster in order to remain competitive. It is a continuous struggle to eliminate unnecessary production costs; improve manufacturing, process and business performance; increase throughput; reduce cycle times; maintain quality; etc. In support of those goals, an adequate level of automation is strived for. Manufacturing Operations Management (MOM) activities coordinate personnel, equipment and material in the conversion of raw materials into final products. Efficient manufacturing operations can be provided by a Manufacturing Execution System (MES). The main goal is to achieve a digital information exchange instead of paper- or spreadsheet-based communication. Nowadays, efficient manufacturing operations without software support has become unthinkable in many cases, due to legal provisions (e.g. tracking & tracing in the food and pharmaceutical industry), high product mix, etc.

Company strategies and business requirements need to be continuously adjusted to follow the latest customer requests and industry trends. Production environments are dynamic, with constantly changing products and manufacturing processes. Today's challenging business environment drives the adoption of Continuous Improvement (CI) initiatives; such as Lean and Six Sigma; in pursuit of business and operational excellence. An MES contains a treasure of information that can be used to support the waste identification and elimination process. Automating information flows in the MOM layer, can reveal opportunities to further improve manufacturing operations by CI initiatives. Benefits can reach further than the initial goal of purely automating information flows. Unfortunately, a lot of companies fail to exploit the full potential of the available data. Literature reports two main problems:

1. **Lack of easy-to-use analytical workbenches on top of real-time data collection:** Shop floor systems emphasize operational aspects and too often neglect to make effective use of the operations data at hand. Analysis and reporting tools, available in MES, may not match the specific requirements of the company. Custom coding of standard tools to support waste identification and elimination can be costly. The integration of company data in standalone Lean software can be time consuming and error prone.

2. **Ease of deployment and use remains a barrier to the adoption of Lean software on the shop floor:** Software systems are believed to lack the necessary flexibility to follow frequent changes and - as result - easily become obsolete. However, the emergence of new technologies (e.g. Service Oriented Architecture (SOA)) makes it more and more possible to apply to the decentralized information needs stated by Lean practitioners. Unfortunately, an AMR research study still shows a limited adoption of Lean IT so far.

Considering the presented combination of Lean tools and techniques (MOM optimization) and MES production control (MOM digitization), a company approach can be gradually classified into three categories: (1) No alignment; (2) Lean MES alignment; and (3) Lean MES integration. In case of no alignment, there is no interaction between both. Lean practitioners gather information manually and avoid the use of IT, even if digital information is available. MES focuses on push control principles and equipment efficiency (e.g. Overall Equipment Effectiveness (OEE)) and neglects value stream aspects such as lead time reduction, load leveling, waste elimination, etc. Eventually, the standalone application of MES and Lean leads to a mismatch between the production control improvements and the shop floor systems. As a result, both strategies don't achieve the anticipated long term benefits. A Lean MES alignment seeks opportunities to effectively combine both strategies in a particular case and make them mutually supportive. When the alignment is automatically maintained on a regular basis, then a Lean MES integration is achieved.

The PhD research proposes a Lean MES framework that structures the requirements to initiate and maintain a Lean MES integration. Within that framework, MES faces a dual task: integrating Lean support and implementing Lean changes. The $95^{th}$ standard of the International Society of Automation (ISA) is an industrial standard for integrating Business and Manufacturing components. As a result, ISA 95 is also proposed as a common information model for MES and Lean. The different components of the Lean MES are described within the Manufacturing 2.0 SOA architecture.

An automated Value Stream Mapping (aVSM) methodology is documented to illustrate a possible application of the Lean MES framework. Because current MES implementations pay little to no attention to flow efficiency, VSM is described in detail. A tool that can automatically perform the complete construction and analysis of VSM is not the goal. The human input will always be the driving force of the exercise. Depending on the historical operations data at hand, MES can deliver meaningful tools to support the analysis. An electronic VSM template can be generated to start the analysis from or to validate the manual result. Additional tools can help identify the waste on the map and suggest future state conditions. Section 3.3 discusses the application of ISA 95 to standardize the Lean MES activities. Representations for product families; VSM icons; typical VSM facts and calculations; and pull production control principles are given. A number of standard algorithms (e.g. identification of product families, current state mapping, line balancing, kanban loop configuration, etc.) make use of those Lean representations to analyze the available operations data. The requirements for a future expansion of the framework with other Lean tools and techniques are listed. In order to impose CI improvements and maintain the Lean MES integration, section 3.4 describes a ISA 95 based change management approach. The approach shows how production control of MES; as Lean IT system; can be implemented (greenfield) or adjusted (brownfield) to follow typical Lean operational changes on the production floor. A number of standard change work flows; that were encountered within the aVSM analysis; are presented: new product introduction, custom reporting and transition to pull flow. Historical data can support these standard changes. This support reduces the change-over time and possible errors within MES, having a positive influence on its Total Cost of Ownership (TCO). It remains a challenge to link the dynamic character of MES to the static nature of Lean. An practical approach is given to realize the change management in function of time.

A lack of real test environments for MES concepts makes it very difficult to validate them. As a first step, the feasibility of the Lean MES framework is checked. Is it able to do what it was designed for? Does the described input (i.e. match Lean with ISA 95 terminology), result in the promised output (i.e. standard Lean support)? First, a simulation example is explored in order to verify the feasibility of the proposed aVSM methodology. However, how accurate the simulation model may be, it is always an abstraction of the reality and can not fully represent the complex dynamics of a production environment. In order to fully validate the Lean MES framework, its ability to support a company to discover opportunities, guide the process, achieve the goals and maintain improvements of CI initiatives must be checked. Two companies were selected for an offline analysis. The selected cases each illustrate a different setting for the application of the framework. Case A features a big beverage manufacturing company. The batch processes are highly automated and production control has already some software support. Case B analyses the situation of a small furniture manufacturing company. The production processes have a highly manual character and the discrete process has currently limited software support. In both cases, the usability of the framework to integrate standard Lean functionality on top of historical data is shown. By transforming the data to standard ISA 95 models, the same tool can be used to support the analysis of both cases. The results of both cases illustrate that aVSM is able to extract valuable information from the available operations data in support of the analysis. However, the two cases are insufficient to really validate the approach. From the experience of both cases, the future validation requirements are set. In addition a benchmarking approach is suggested to evaluate MES research results.

Within the proposed Lean MES framework, aVSM is the first step toward a standard analytical workbench on top of real-time data collection. By expanding the CI support, a standard collection of tools can be developed to enable full scale MOM support. A short description is given for the integration of TPM. Other options are TQM, Six Sigma, Lean selection and planning intelligence, etc. Each system that speaks and understands ISA 95 could be plugged in to use the predetermined set of tools to optimize MOM. An MES, using ISA 95 as underlying data model, is commercially available. The possibility must be investigated to implement a pilot aVSM tool in the software. That would enable a larger scaa¡le validation of the proposed aVSM methodology in particular and the Lean MES framework in general.

# 1
# Introduction

## 1.1 Research Area

Production environments face constant pressure to produce better and faster in order to remain competitive. It is a continuous struggle to eliminate unnecessary production costs; improve manufacturing, process and business performance; increase throughput; reduce cycle times; maintain quality; etc. In support of those goals, an adequate level of automation is strived for. Administration and production were typically treated as two separate islands. The difficulty of integrating those two completely different worlds, has had its share of attention in literature so far and is commonly referred to as Manufacturing Operations Management (MOM). The main goal is to achieve a digital information exchange instead of paper- or spreadsheet-based communication. Nowadays, efficient manufacturing operations without software support has become unthinkable in many cases, due to legal provisions, high product mix, etc. Over the years, production departments have always favored the development of custom-made software applications, due to a lack of attention paid by information system specialists to the shop floor. However, the difficulty of integrating these multiple point systems has brought software providers to package multiple execution management components into single and integrated solutions or a so-called Manufacturing Execution System (MES). The current MES research mainly focuses on the following topics:

1. **Architecture and models:** There have been numerous attempts to create (open) frameworks to ease the actual implementation and integration of a general-purpose and efficient MES. Multi-Agent Systems (MAS) have received particular attention because of their distributed organization, high modularity and simplicity of imple-

mentation. One of the most fruitful and widespread approaches formalizing the use of agents in manufacturing systems has been developed in the Holonic Manufacturing Systems (HMS) (Valckenaers et al., 1994), where a 'holon' is defined as the association of a software agent with a physical device or a set of physical devices. Recent MES research efforts focus on an appropriate architecture to support reconfigurable, flexible, agile and adaptable manufacturing systems (Zhaohui et al., 2009; Gang et al., 2010) in order to follow manufacturing changes quickly and adequately. An example is the step towards self-organizing manufacturing control.

2. **Standardization and integration:** A lot of components are available within MOM. Standardization organizations and practitioners put a lot of effort in the integration aspects of MES. Industrial standards (ISA 95, 2000) and new technologies; such as SOA (MESA International, 2008b); try to integrate all components to seamlessly one enterprise IT system. For example, multinationals face the challenge to adopt a multi-site MES (MESA International, 2008a).

3. **Dynamics and optimization of Production Planning and Control (PPC):** The layered PPC approach gets a lot of attention of the control theory and operations research communities. Executing and optimizing production schedules in the presence of unforeseen disruptions on the shop floor result in a complex dynamical behavior (Aytug et al., 2005). Tackling those issues requires new algorithms, improved metrics for performance assessment, self-learning systems, etc.

Literature lacks sufficient attention on the main goal of MES: creating visibility on the shop floor. That is crucial in order to facilitate operators to see the bigger picture and to anticipate the impact of their decisions. MES contains a treasure of information that can be used to support that decision making process. Automating information flows in the MOM layer, can reveal opportunities to further improve manufacturing operations. Benefits can reach further than the initial goal of purely automating information flows. The extra visibility can lead to additional value creation. Unfortunately, most companies fail to exploit the full potential of the available data. Literature reports a lack of easy-to-use analytical workbenches that can be used on top of real-time data collection (Masson and Jacobson, 2007).

Company strategies and business requirements need to be continuously adjusted to follow the latest customer requests and industry trends. Production environments are dynamic, with constantly changing products and manufacturing processes. Today's challenging business environment drives the adoption of Continuous Improvement (CI) initiatives; such as Lean and Six Sigma; in pursuit of business and operational excellence. The main research area's concerning Lean are:

1. Apply the philosophy to new disciplines, e.g. Lean information management (Hicks, 2007)

2. Modify tools and techniques to fit different environments, e.g. POLCA (Suri, 2003)

3. Support appropriate selection and planning of Lean tools, e.g. classification scheme for tools by impact on typical problems (Pavnaskar et al., 2003)

Originally, Lean practices were considered to be based on purely manual efforts. However, Lean and IT are more and more claimed to be interdependent and complementary (Riezebos et al., 2009). Some research has already been done on the combination between the Lean Production System and ERP (Goddard, 2003; Sandras, 2003; Bell, 2005). The (near) real-time information flow of the MES looks like a better fit for Lean than the batch oriented ERP systems. The everlasting change within a production environment lays a dual task on MES: supporting the change process, but also controlling the achieved improvements. By imposing the new way of working, the improvements can be maintained. An issue that has not yet received the full attention it deserves, is MES/MOM change management. No research has been found that describes the post-implementation aspects of MES. Although this phase represents a significant part of the Total Cost of Ownership (TCO) of such systems. The usability of the software system highly depends on its ability to reflect the current manufacturing situation. An MES should always present the data wished for by the user, at the right format, at the right time, at the right place. The CI of MES itself is important to keep the system reliable and to standardize the new way of working.

## 1.2 Research Questions

This doctoral research combines the two under researched topics described above - MES visibility and Lean IT - and provides an answer to the following questions:

1. **What is (and can be) the role of an MES in the CI cycle within MOM?**
   No previous research on this topic has been found, but software vendors already anticipate this Lean MES story. Stand-alone applications are already developed to automate and support Lean practices, such as eKanban, Six Sigma programs, Visual Management screens, Key Performance Indicator (KPI) generators, etc. More and more MES software vendors have some Lean support incorporated. Every product folder has some reference to the Lean philosophy. It must be that there is need for an MES that supports the Lean philosophy. A study of AMR shows a limited adoption of Lean Information Technology (IT) so far. Ease of deployment and use remains a barrier to the adoption of Lean software on the shop floor. As a first step in this research, the role that an MES can play in the CI cycle of the Lean philosophy is described.

2. **What is the concept of a Lean MES framework?**
   As Lean and MES are mutually supportive, the concept of a Lean MES framework is proposed. This framework structures a standard approach to align the digitization of information flows with Lean efforts within MOM. Depending on the legacy systems of the company, a distinction must be made between greenfield[1]

[1]The project can start from scratch. There are no legacy systems that need to be updated or integrated.

and brownfield[2] projects. The applicability of the ISA 95 standard as starting point for this framework is evaluated. The possibility to extend the definitions with Lean philosophy and integrate Lean tools and techniques is discussed.

3. **How can MES be restructured to support standard decision making?**
To enable standard decision making support, two things are necessary. First of all, Lean tools and CI initiatives must be defined within the Lean MES framework. Based on a common data model (ISA 95), these tools would enable standard analysis opportunities. This generic approach to the analytical workbench on top of real-time data collection, could facilitate a wide range of manufacturing companies. Based on the desired functionality during the Lean journey, specific data and information requirements can be configured to support the CI initiatives. In a second step, the available (or future) data must be transformed (or made available) within the standard data model format. The support for a popular Lean tool, Value Stream Mapping (VSM), is explored as an example. A procedure is described in order to add other Lean tools and techniques in the future.

4. **What is a feasible change management approach for MES to follow typical Lean changes?**
The usability of MES highly depends on its ability to reflect the current manufacturing situation. The CI of MES itself during the Lean journey is important to keep the system reliable. Goodness of fit and flexibility are often conflicting goals. Custom coding can deliver an ideal system at the time but generate excessive costs to maintain, reconfigure or adapt the system in the future. A good balance must be strived for to minimize the TCO. Within the Lean MES framework, a change management approach is presented based on ISA 95. It provides reconfiguration options for typical Lean changes. Standard model changes can be constructed to automate these transitions. As an example, the roadmap is described to shift production control from push to pull.

## 1.3 Research Methodology

Figure 1.1 shows the research methodology used within this doctoral research. Chapter 2 provides a general introduction and literature review on the main topics, MOM and Lean. After a discussion about the combination of both Lean and IT, the role of MES in the CI cycle (and vice versa) is evaluated. Chapter 3 structures the proposed Lean MES framework. The MOM framework provided by ISA 95 is believed to deliver the necessary components to identify and structure the alignment between Lean and MES. Mapping MES and Lean activities onto the same framework brings valuable insights about their dependency. Each company situation is unique and consists of a subset of standard MES functionalities and standard Lean tools and techniques. An extension of the ISA

[2] The company has one or more legacy systems that need to be replaced, updated and/or integrated. In most cases, this limits the degrees of freedom for the new solution.

95 models is proposed to enable standard data and analysis support from MES for Lean purposes. In addition, an MES change management approach is suggested to control the achieved improvements. In chapter 4, a simulation example is constructed to verify the concept of the Lean MES framework. This pilot implementation must verify if the presented framework is able to do what it is designed for. Does the presented match between Lean and ISA 95 terminology result in standard Lean support? Simulation software (i.e. Flexsim$^{TM}$) is used to model the manufacturing process and part of the MOM support. The lack of real test environments for MES concepts, makes it very difficult to validate the proposed approach. The simulation case is a good indication of the feasibility of the method. But, how accurate the simulation model may be, it is always an abstraction of the reality and can not fully represent the complex dynamics of a production environment. In order to fully validate the Lean MES framework, its ability to support a company to discover opportunities, guide the process, achieve the goals and maintain improvements of CI initiatives must be checked. Two companies were selected for an offline analysis. The number of cases is limited, due to the time consuming nature of the analysis. The selected cases each illustrate a different setting for the application of the framework. Case A features a big beverage manufacturing company. The batch processes are highly automated and production control has already some software support. Case B analyses the situation of a small furniture manufacturing company. The production processes have a highly manual character and the discrete process has currently limited software support. In both cases, the usability of the framework to integrate standard Lean functionality on top of historical data is shown. However, the two cases are insufficient to really validate the approach. From the experience of both cases, the future validation requirements are set. Chapter 5 concludes and mentions further research opportunities.

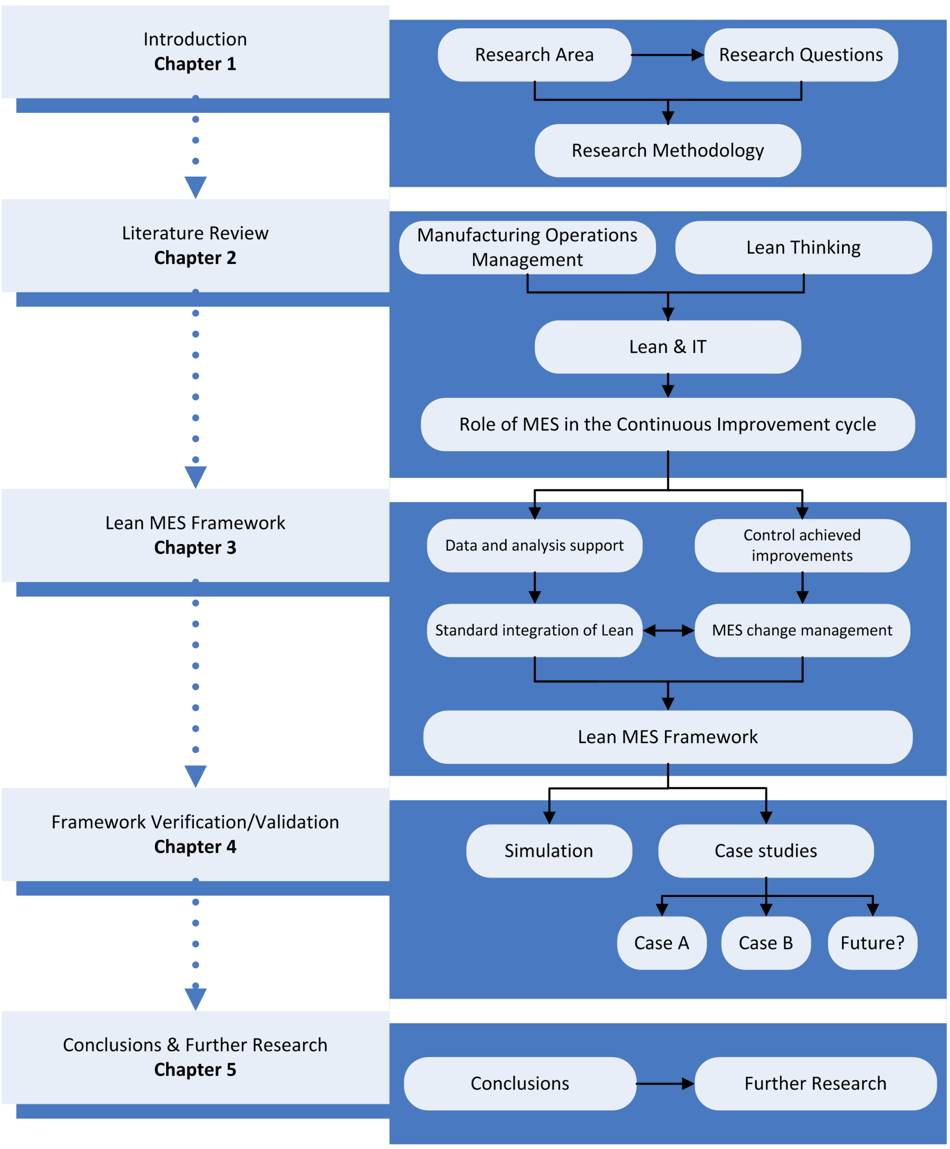


*Figure 1.1: The research methodology of this doctoral research*

## 1.4 Publications

### 1.4.1 Publications in international journals (A1 - appearing in Web of Science)

3. **J. Cottyn**, H. Van Landeghem and K. Stockman. A Framework to Initiate and Maintain a Standard Lean Manufacturing Execution System Integration. *International Journal of Production Research*, Under review, Submitted: January 2012.

2. **J. Cottyn**, H. Van Landeghem, K. Stockman and S. Derammelaere. A Method to Align a Manufacturing Execution System with Lean Objectives. *International Journal of Production Research*, 49(14):4397-4413, June 2011.

1. (W. Waegeman, **J. Cottyn**, B. Wyns, L. Boullart, B. De Baets, L. Van Langenhove, J. Detand. Classifying Carpets based on Laser Scanner data. *Engineering Applications of Artificial Intelligence*, 21(6):907-918, September 2008.)

### 1.4.2 Publications in peer-reviewed international conferences (P1 - appearing in Web of Science)

3. **J. Cottyn**, H. Van Landeghem, K. Stockman and S. Derammelaere. The Role of Change Management in a Manufacturing Execution System. *International Conference on Computers in Industrial Engineering (CIE) 41, Proceedings*, 453-458, Los Angeles, USA, October 2011.

2. **J. Cottyn**, H. Van Landeghem, K. Stockman and S. Derammelaere. The Combined Adoption of Production IT and Strategic Initiatives: Initial Considerations for a Lean MES Analysis. *International Conference on Computers in Industrial Engineering (CIE) 39, Proceedings*, vols 1-3, 1629-1634, Troyes, France, July 2009.

1. (**J. Cottyn**, T. Govaert and H. Van Landeghem. Alternative Line Delivery Strategies Support a Forklift Free Transition in a High product Variety Environment. *International Workshop on Harbor Maritime and Multimodal Logistics Modeling and Simulation (HMS 2008), Proceedings*, 55-60, Campora S. Giovanni, Calabria, Italy, September 2008.)

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5. **J. Cottyn**, H. Van Landeghem, K. Stockman and S. Derammelaere. The Role of a Manufacturing Execution System during a Lean Improvement Project. *13th International Conference on Modern Information Technology in the Innovation Processes of industrial enterprises (MITIP), Proceedings*, 1, 317-326, Trondheim, Norway, June 2011.

4. T. Desmarey, K. Degryse and **J. Cottyn**. Support for Manufacturing Operations in Belgian SMEs: One Size Fits All?. *13th International Conference on Modern Information Technology in the Innovation Processes of industrial enterprises (MITIP), Proceedings*, 1, 139-148, Trondheim, Norway, June 2011.

3. K. Degryse, T. Desmarey and **J. Cottyn**. A Method to Support SMEs to Optimize their Manufacturing Operations. *13th International Conference on Modern Information Technology in the Innovation Processes of industrial enterprises (MITIP), Proceedings*, 1, 129-138, Trondheim, Norway, June 2011.

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1. **J. Cottyn**, K. Stockman, and H. Van Landeghem. The Complementarity of Lean Thinking and the ISA 95 Standard. *In WBF European Conference: Bridging the Divide between IT and Manufacturing*, Barcelona, Spain, November 2008.

### 1.4.4 Other (A4)

2. **J. Cottyn** and T. Desmarey. Gestandaardiseerde Productiesoftware op Maat van uw Bedrijf: Een Contradictie?. *Technology Upgrade*, 7, 10-12, February 2010.

1. **J. Cottyn** and H. Capoen. MES: Manufacturing Execution System - De Cruciale Brug tussen Management en Productie. *Technology Upgrade*, 4, 19-21, February 2009.

# 2
# Literature Review

*This chapter provides a general introduction to the research topic, necessary to understand the contribution of this work. Section 2.1 describes the crucial integration of administration and production: Manufacturing Operations Management (MOM). It is a broad domain, where each business case requires an individual and unique approach. The main goal is to increase the efficiency by deploying digital information exchange and activity support instead of paper- or spreadsheet-based systems. This digital support is given by a Manufacturing Execution System (MES). Typically, this software is modular and support is implemented incrementally. Standardization plays a very important role in this MOM evolution. The Lean thinking philosophy is introduced in section 2.2. The essence of Lean is specifying value and - by doing so - simultaneously uncovering waste. A number of Lean tools and techniques are described in order to illustrate the Continuous Improvement (CI) cycle towards perfection. Lean advocates strongly defend a purely manual approach. However, as MES and Lean both pursue the same objectives, the combination of Lean and Information Technology (IT) looks unavoidable and is discussed in section 2.3. At one hand, a Lean look at IT through Lean information management and Lean software development creates new perspectives. On the other hand, software support for Lean can improve the usability and efficiency of existing (manual) tools and techniques. As a lot of digital information is available in many cases anyway, it can partly eliminate the time consuming and error prone manual data collection and entry. At least, it can be used to support or validate the manual efforts. The effect of IT is discussed for popular tools and techniques, such as Value Stream Mapping (VSM), Kanban and visual management. Merging the Lean IT support within MOM, suggests a combination between Lean and MES. Section 2.4 discusses the role of an MES in the CI cycle. Automating information flows in the MOM layer - being the main goal of MES - can reveal opportuni-*

*ties to further improve manufacturing operations. As CI opportunities and initiatives are countless, the selection and implementation of the ideal steps during the Lean journey - towards perfection - is no easy task. The proposed Lean MES framework must structure and support this continuous process. The ability of the ISA 95 standard to form the basis of the Lean MES framework is examined. ISA 95 must enable data and analysis support for CI and guide MES/MOM change management to control the achieved improvements. Some concluding remarks are given in section 2.5.*

## 2.1 Manufacturing Operations Management (MOM)

### 2.1.1 Definition

In a continuous struggle to remain competitive, manufacturing companies try to boost performance, improve quality and cut costs. In order to achieve that, software support is essential (Aberdeen Group, 2005b). The concept of Computer Integrated Manufacturing (CIM) (Harrington, 1973) started with computerized work cells and evolved from Computer-Aided Design and Computer-Aided Manufacturing (CAD/CAM) through communication protocols to the current definition of CIM: the integration of the complete factory throughout all functional departments (Nagalingam and Lin, 2008). A Production/Process Control System (PCS) ensures efficient daily manufacturing activities, resulting in qualitative finished products. Enterprise Resource Planning (ERP) software maintains important business data and supports the administrative processes. Administration and production were typically treated as two separate islands[1]. Figure 2.1 shows the gap in between them in the CIM pyramid. The difficulty of integrating those two completely different worlds, has had its share of attention in literature so far (MESA International, 1997; Brandl, 2002; Kjaer, 2003; Macedo et al., 2004; Morel et al., 2007; Louis and Alpar, 2007; Saenz de Ugarte et al., 2009) and is now commonly referred to as Manufacturing Operations Management (MOM). A number of characteristics of the production and administration level are difficult to match:

1. **Time constant:** The higher in the pyramid, the bigger the time constant. Management level mainly considers aspects on the long term: years, months and weeks. They prefer monthly Overall Equipment Effectiveness (OEE) values over the current machine states. An operator on the production floor, on the other hand, is more interested in immediate information. The time constant is here rather minutes, seconds or less. A machine failure must be detected immediately and, if possible, the necessary information to fix it should be readily available.

2. **Amount of data:** The higher in the pyramid, the bigger the amount of data required. Management needs large batches of data to extract aggregated Key Performance Indicator (KPI) information. Production prefers small amounts of data that clearly indicate the necessary information, e.g. machine is active or not.

3. **Basic functionality:** Administration processes order and make deliveries. The necessary products are produced by production control. Administration and production both try to optimize their own operation[2], considering the other one as a black box. That can only result in a suboptimal overall performance. The company's business & financial and operational metrics should be aligned (Industry Directions, 2006).

[1]Historically, they belong to different departments. The IT department is responsible for administrative software, while engineering ensures efficient production control. IT and production managers are suddenly forced to work together towards a joint solution. Conflicting interests can turn this task into a difficult bargain.

[2]Administration and production are both using their own performance metrics based on quality, cost and delivery information. Business and financial metrics are preferred by administration, production focuses on operational metrics.

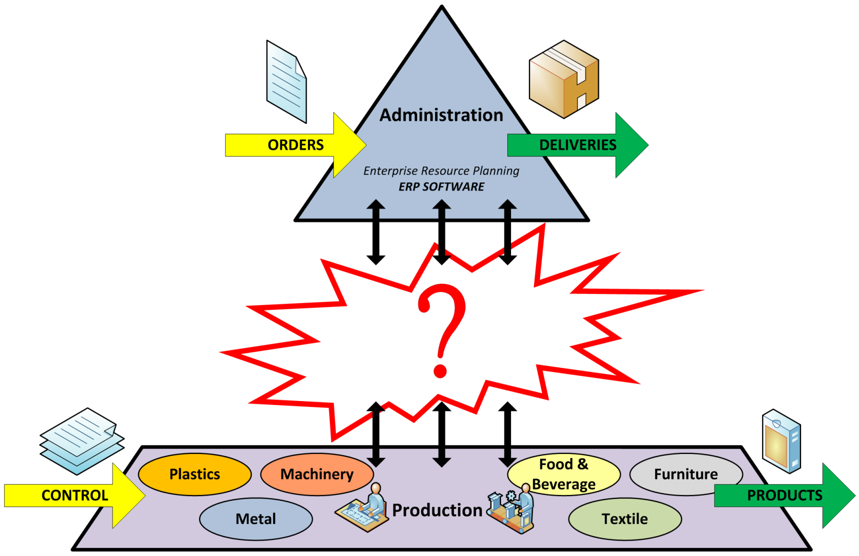



*Figure 2.1: Manufacturing Operations Management: the gap between the administration level and the production level*

The integration issue was already going on for several years when the MOM definition was introduced by the International Society of Automation (ISA) (ISA 95, 2000), providing a functional description apart from the available software applications:

> *The activities of manufacturing operations management are those activities of a manufacturing facility that coordinate the personnel, equipment, material, and energy in the conversion of raw materials and/or parts into products. Manufacturing operations management includes activities that may be performed by physical equipment, human effort, and information systems. Manufacturing operations management is subdivided into four categories: production operations management, maintenance operations management, quality operations management, and inventory operations management.*

Besides providing a consistent terminology, two additional aspects out of the above definition confirm the value of the object models of the $95^{th}$ standard of the International Society of Automation (ISA 95) for a full company MOM analysis:

1. **MOM structures all activities and information flows, whether they are performed manually or automatically:** All sorts of activities and information flows are covered in ISA 95. Activities can be performed manually (e.g. paper-based scheduling), semi-automatically (e.g. spreadsheet-based scheduling) or automatically (e.g. use of a scheduler). Information flows can be manual (e.g. dispatch and follow up production orders on paper), semi-automatic (e.g. scan production order

activities at the work stations) or automatic (e.g. dispatch and follow up production orders in real-time on a touch panel).

2. **The functionality within the MOM layer is subdivided by activity, not by organizational structure of the company:** Four activities are structured: production, maintenance, quality and inventory. Each one consists of a number of subactivities. One solution can span multi-site, multi-country and multi-cultural environments (ISA 95, 2000; Wissink, 2007). It is not stated which system is responsible for each activity, so the actual system can be a customized solution, a combination of integrated subsystems, ERP extensions, dedicated systems, etc.

Nowadays, efficient manufacturing operations without software support have become unthinkable in many cases, due to legal provisions (e.g. tracking & tracing in the food industry), high product mix, etc. The main goal is to achieve a digital information exchange instead of paper- or spreadsheet-based communication, or short: digital MOM. Different kinds of software tools can also collect and analyze real-time data and turn them into valuable knowledge to further optimize manufacturing operations. Production departments have always favored the development of custom-made software applications, due to a lack of attention paid by information system specialists to the shop floor. However, the difficulty of integrating multiple point systems has brought software providers to package multiple execution management components into single and integrated solutions (Saenz de Ugarte et al., 2009). The emergence of functional (MESA International, 1997) and integration (ISA 95, 2000) standards defined the structure of MOM in CIM more closely. That has proven to be an important step from custom-made to pseudo-standard (configured) software solutions. Over the years (and even today), a lot of acronyms have been (and are still being) used to describe these software systems (Unger, 2001; Flakol, 2008; Nagalingam and Lin, 2008). Depending on the main functionality of the system, a Manufacturing Execution System (MES), a Maintenance Management System (MMS), a Warehouse Management System (WMS), a Laboratory Information Management System (LIMS) or a Logistics Execution System (LES) can be distinguished. However, as one software solution can cover multiple activities, the term MES is generally used to describe the complete software system operating the MOM layer. In this work, the term MES[3] - as a synonym for Manufacturing Operations Management Software (MOMS) - will be used to denote the (collection of) software system(s) operating the MOM layer. Figure 2.2 shows the location of these pseudo-standard software solutions within the CIM pyramid. Standard integration with ERP software (administration) can be achieved by using Business to Manufacturing Markup Language (B2MML). The integration with PCS (consisting of a combination of different Programmable Logic Controller (PLC), Distributed Control System (DCS) and/or Supervisory Control and Data Acquisition (SCADA) control systems) can be standardized using OLE for Process Control (OPC).

[3]This notation is used to clearly differentiate between the framework (MOM) and the application (MES).

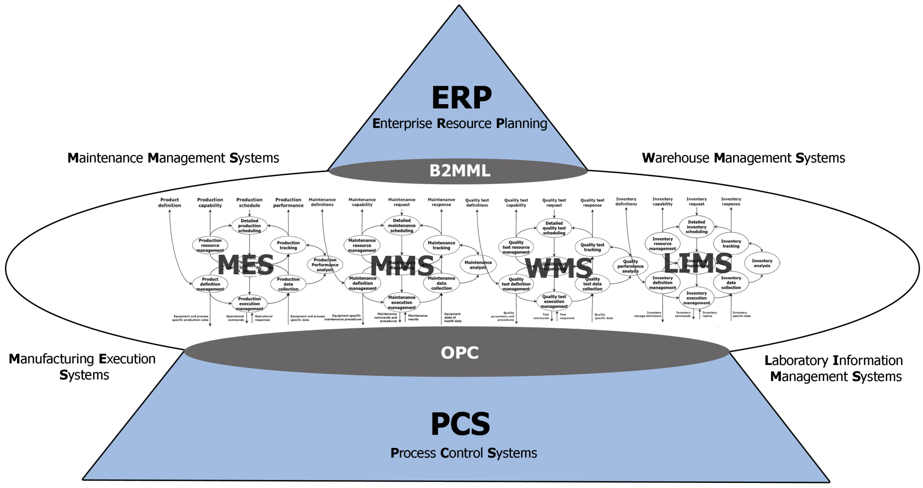



*Figure 2.2: Pseudo-standard software solutions operating within the MOM layer on the different activities: maintenance, production, inventory and quality*

### 2.1.2 Evolution

Through digitization and optimization, MOM must continuously evolve in order to remain efficient within a changing and demanding manufacturing environment. The digitization of manufacturing operations typically follows a phased, instead of a 'big bang' approach (Nagalingam and Lin, 2008). Through low hanging fruits, the important buy-in at each level in the organization can be achieved (CDC Factory, 2007). The initial MES adoption usually consists of functionalities like automated data collection, order tracking, material tracking & tracing, KPI reporting, etc. The content of this first digitization step highly depends on the company's most urgent needs. Through further innovation steps, additional activities are supported and information flows are automated. Optimization covers all improvement initiatives that alter the content of MOM in order to boost performance. The current way of working is reviewed and adjusted[4] where considered necessary.

The initial adoption and incremental innovation steps require a typical system development life cycle. The following main phases can be distinguished in an MES project life cycle: (1) awareness, (2) feasibility, (3) specification, (4) selection, (5) implementation and (6) maintenance. Due to the broad scope of MOM, tackling such a project is far from trivial. How can be determined what, why and how MOM activities and information flows can be digitized? A lot of software systems and approaches are available, each one backed up by a number of success stories. The truth is: there is no predefined MOM path to success. Contingency theory operates from the assumption there is no 'one best way'

[4]These adjustments can be as well fine-tuning the current digital support, as reconsidering factory layout, SOP, etc. Standard tools and techniques (PDCA, DMAIC, SMED, VSM, etc.) of popular management philosophies (Lean, Six Sigma, etc.) can be used for this purpose.

to carry out a task. The implementation is contingent on a number of factors. Crandall and Crandall (2010) state that contingency theory maintains that one best solution does not exist for even similarly related operations management problems. Instead, the success is contingent on internal factors within the organization and the manner in which it is implemented. Their work applies the theory to management improvement programs such as Just In Time (JIT), Total Quality Management (TQM) and Six Sigma. In addition, they also refer to the implementation of ERP. ERP systems represent an approach that requires a company to adopt best practices, but not necessarily those best suited to the company, possibly resulting in failure. This reasoning is even more true when considering MOM software implementations (Scholten, 2007b). Contingent factors are for example: company size, manufacturing sector, manufacturing strategy and Standard Operating Procedures (SOP). Software vendors that configure standard MES solutions usually present results from previous projects to persuade new customers. However, it is important to differentiate between the company that originates the MOM implementation, and the companies that follow later on with their own version. The originator is the first company that successfully implements the system. If the followers, using the same software solution, are also successful, it is most likely that they operate similar to the originators. That explains why most MOM software solutions specialize in specific industries, such as: pharmaceutical, food & beverage, metal, liquid bulk storage, etc. However, when extended into businesses different from the originator, the level of success may vary and, in some cases, the implementation may actually be considered a failure. Contingency theory maintains that managers should match the solution carefully with the needs of the organization. Due to the uniqueness of each MOM implementation, a thorough analysis is needed. Setting up User Requirements Specification (URS) documents is a crucial first step. By modeling the AS-IS situation, everyone is forced to question the current way of working. Problems get discovered and inefficiencies revealed, resulting in a TO-BE situation. The URS documents define the conditions for MES selection. Consultants and practitioners have developed a number of structured approaches for the selection process, e.g. based on ISA 95 (Scholten, 2007a).

When the requirements are set, a difficult challenge remains in finding a feasible solution. Goodness of fit[5] and flexibility of software are often conflicting goals. Custom coding can deliver an ideal system at the time but generate excessive costs to maintain, reconfigure or adapt the system in the future. At the other hand, a standard system may require to alter the normal way of working of the company and result in an efficiency decrease or perhaps a loss of competitive advantage. A good balance must be strived for to minimize the Total Cost of Ownership (TCO). Focusing on this optimal point must compensate for the natural tendencies towards over-complication, over-automation and rigidity (Bell, 2005). A standard solution that enables the company specific way of working through configuration and minor custom coding reduces costs and could be a good fit (Fraser, 2009). Justifying the investment towards management is yet another story. Mak-

[5]Measures of goodness of fit typically summarize the discrepancy between the usefulness of the model/system at hand (here: MES) and the actual model/system requirements (here: URS).

ing an investment analysis for MOM software - and even Information Technology (IT) in general (Fichman, 2004; Närman et al., 2009; Banakar and Tahriri, 2010) - is very hard. It is not trivial to put featured benefits against the high installation costs and possible risks (Nagalingam and Lin, 1997; Liang and Li, 2008; Nasarwanji et al., 2009; Fraser, 2009). In practice, results of other company cases are frequently used as references. But every company is different and such a comparison is only a wild guess. That is an important reason why in many cases management is rather unwilling to take the risk.

### 2.1.3 Role of standardization

The Manufacturing Enterprise Solutions Association (MESA) is an international organization founded in 1992 by MES solution providers to promote the applicability of their software systems. The focus of the organization shifted over the years to Operational Excellence (OPEX). By using a combination of IT and best management practices, production processes will improve and business results increase. MESA supports manufacturing companies in order to realize the opportunities of IT within production environments. By publishing and presenting best practices, manufacturers get to know which measures other companies have taken to be successful. MESA learns them to be successful in selecting and applying technology. In analogy to the given definition of MOM, MES is defined as:

> *Manufacturing Execution Systems (MES) deliver information that enables the optimization of production activities from order launch to finished goods. Using current and accurate data, MES guides, initiates, responds to, and reports on plant activities as they occur. The resulting rapid response to changing conditions, coupled with a focus on reducing non value-added activities, drives effective plant operations and processes. MES improves the return on operational assets as well as on-time delivery, inventory turns, gross margin, and cash flow performance. MES provides mission-critical information about production activities across the enterprise and supply chain via bi-directional communications.*

The MESA efforts meant an important step towards functional standardization, where before its emergence every software editor had its own definition of MES based on the capabilities of his own tools or on the expectations of his customers. To meet the needs of a variety of manufacturing environments, MESA identified 11 principal MES functions (MESA International, 1997) in its functional model (Figure 2.3).

1. The function **Resource Allocation and Status** controls all relevant resources: machines, materials, equipments, personnel, etc. In order to fulfill the current production schedule, the necessary resources are allocated. A detailed history is maintained.

2. **Operations/Detail Scheduling** is responsible for drawing an optimal schedule taking into account the available resources and a number of company-specific parameters (e.g. priorities, maintenance, changeovers, etc.).

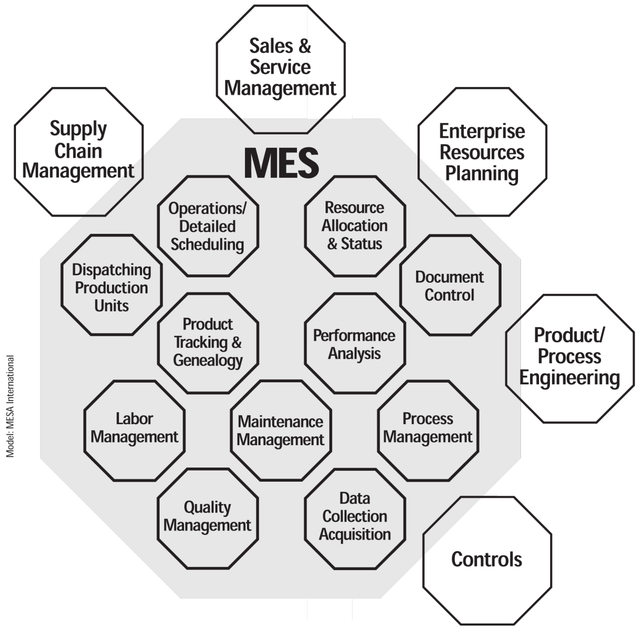



*Figure 2.3: The MESA functional model with 11 principal MES functions (MESA International, 1997)*

3. Production units are managed by the function **Dispatching Production Units**. The necessary information (e.g. batches, lots, orders, etc.) are dispatched to the units and are displayed - in order of priority - in their work queue. When sudden changes or unexpected circumstances occur, the current schedule is adjusted in real-time.

4. **Document Control** maintains and displays all relevant information to operators at the correct location within production. Examples are: drawings, SOP, batch records, regulatory requirements for environment, health and security.

5. The function group **Data Collection/Acquisition** is responsible for the collection and logging of production related data.

6. **Labor Management** provides the status of personnel in and up-to-the-minute time frame. This includes time and attendance reporting, certification tracking, as well as the ability to track indirect activities as a basis for activity based costing. It may interact with resource allocation to determine optimal assignments.

7. **Quality Management** provides real time analysis of measurements collected from manufacturing to assure proper product quality control and to identify problems requiring attention. It may recommend action to correct the problem, including correlating the symptom, actions and results to determine the cause.

8. The function **Process Management** monitors production and either automatically corrects or provides decision support to operators for correcting and improving in-process activities. These activities may be intra-operational and focus specifically on machines or equipment being monitored and controlled as well as inter-operational, which is tracking the process from one operation to the next. It may include alarm management to make sure factory personnel is aware of process changes which are outside acceptable tolerances.

9. **Maintenance Management** tracks and directs the activities to maintain the equipment and tools to insure their availability for manufacturing and provide scheduling for periodic or preventive maintenance as well as the response (alarms) to immediate problems. It maintains a history of past events or problems to aid in diagnosing problems.

10. The visibility to where work is at all times is provided by **Product Tracking and Genealogy**. Status information may include who is working on it; components, materials by supplier, lot, serial number, current production conditions and any alarms, rework, or other exceptions related to the product. The online tracking function creates a historical record, as well. This record allows traceability of components and usage of each end product.

11. **Performance Analysis** provides up-to-the-minute reporting of actual manufacturing operations results along with the comparison to past history and expected business result. Performance results include such measurements as resource utilization, resource availability, product unit cycle time, conformance to schedule and performance to standards. Draws on information gathered from different functions that measure operating parameters.

ISA is a non-profit organization that is founded in 1945 and develops automation standards. ISA 95 (ISA 95, 2000) is the $95^{th}$ standard published by ISA, entitled: 'Enterprise-Control System Integration'. The contribution of ISA 95 is in essence the formalization of the exchange around the manufacturing system to other areas of the company. It can be used for the design of information flows between shop floor level applications and those of a higher level. In addition ISA 95 delivers a consistent terminology. Although these are in fact the main contributions, its practical benefits reach a lot further and deserve some extra attention. ISA 95 provides a number of object models and terminology that serves as a common model of integration, a standard terminology to define system requirements and integration between different software systems. ISA 95 consists of six parts[6]. Each part focuses on a specific aspect of the MOM (or enterprise-control system) integration:

- **Part 1: Models and Terminology**
  General models that determine the role of MOM and the structure and content of the information exchange between MOM and other business systems.

[6] Whereof two parts are still unpublished.

- **Part 2: Object Model Attributes**
  Definition of attributes for the object models of part 1: Material, personnel, equipment, process segment, production schedule, production performance, etc.

- **Part 3: Activity Models of MOM**
  Overview of the activities and information flows within the MOM layer (Figure 2.4).

- **Part 4: Object Models and Attributes of MOM** (under development)
  Definition of the structure and content of the information flows within the MOM layer.

- **Part 5: Business to Manufacturing Transactions**
  Description of a message-based communication between the MOM and the business layer.

- **Part 6: MOM transactions** (to be developed)
  Description of the communication within MOM.

For now, only the activity models of MOM (Figure 2.4) will be briefly discussed, because they will be frequently used in the next chapter. The other models will be clarified later on when needed. ISA 95 uses the basic MESA definitions of MES (Figure 2.3) and expands them by adding activity details and tasks and extends them into additional operational areas; such as maintenance, quality and inventory. At the top, the information exchange with business applications is defined, as generally discussed in part 1 of ISA 95. At the bottom of figure 2.4, the link is given to level 1 & 2, manufacturing control. All MOM activities in between are structured through interconnected bubbles. Each bubble represents a specific activity, each arrow an internal information flow. This general MOM overview makes the model ideal for analysis purposes. When zooming in on a certain activity, in- and output of the functionality can be reviewed in more detail. As an example, figure 2.4 gives a more detailed view on the activity *Detailed Production Scheduling*. Detailed production scheduling is defined as the collection of activities that take the production schedule and determine the optimal use of the available resources to meet the production schedule requirements. A detailed production schedule is based upon the requirements defined in the production schedule, the product definition and the resource capability. It also uses information from production tracking activities to account for actual Work In Process (WIP). The detailed production schedule may be provided either on demand or on a predefined time or interval. Unanticipated events such as equipment outages, manpower changes and/or raw material availability changes can trigger a recalculation. The result may be provided to people (e.g. outprint for production manager) or to applications (e.g. production dispatching module).

The different standards are not intended to represent an actual implementation of MES. They rather provide a method, a way of working. They propose a consistent framework for such systems. The purpose of the models is to identify possible activities and information flows within manufacturing operations. There have been numerous attempts

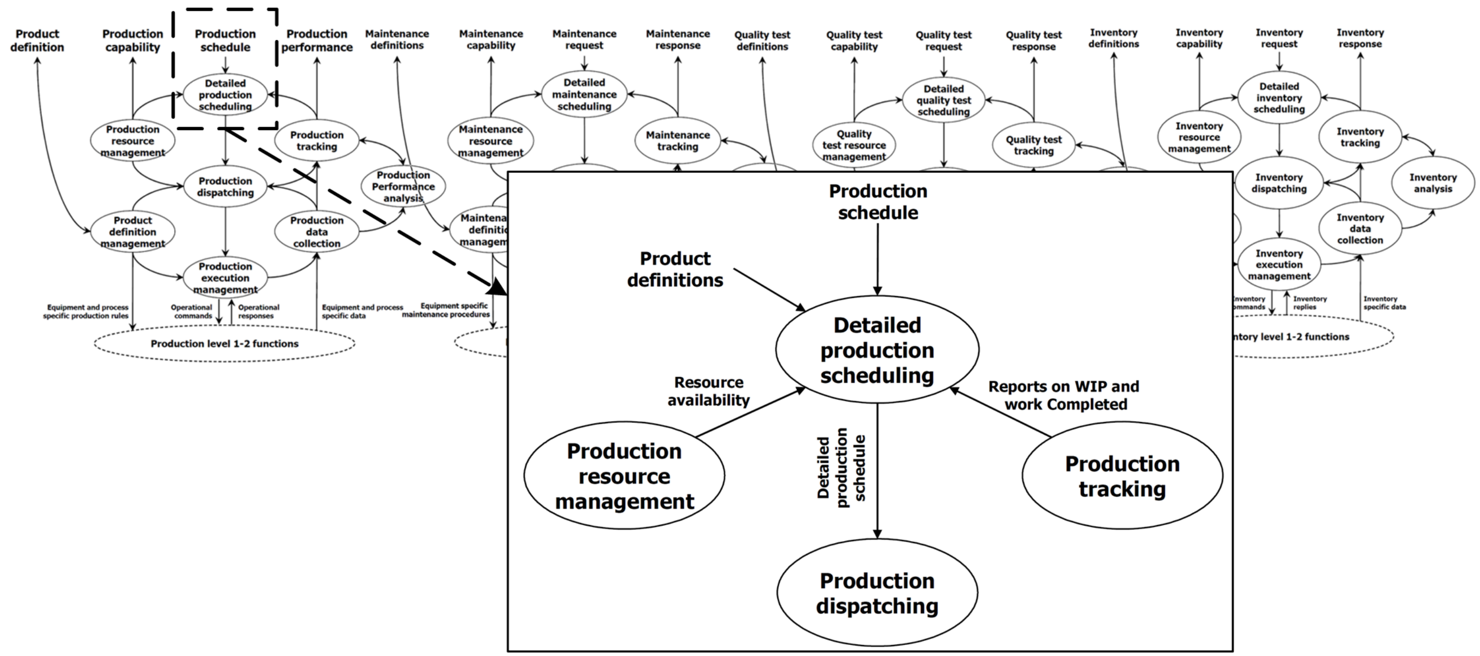



*Figure 2.4: The activity models of ISA 95 part 3, zoomed in on Detailed Production Scheduling (Source: ISA 95 (2000))*

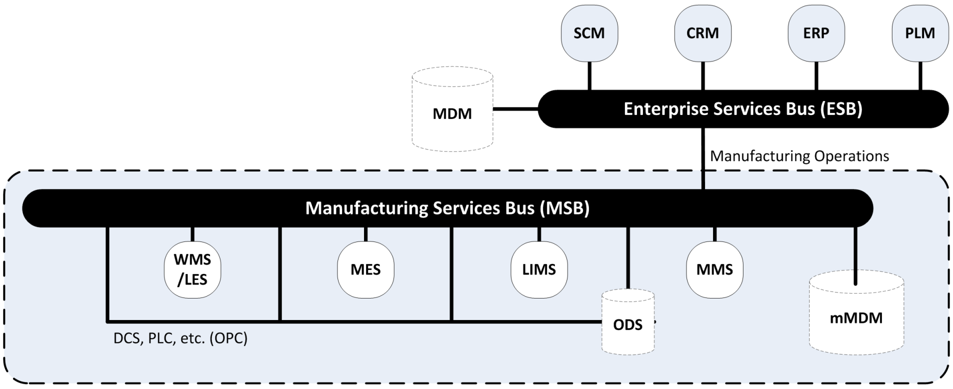



*Figure 2.5: The Manufacturing 2.0 architecture approach highlights the requirement for a separate manufacturing services bus (MSB) for manufacturing operations (Source: MESA International (2010b))*

to create frameworks to ease the actual implementation and integration of an CIM system environment. A number of open frameworks for MES were developed and adjusted over the years (Sematech, 1996; Cheng et al., 1999; OpenMES, 2000; Choi and Kim, 2002; Pabadis, 2002; Heragu et al., 2002; Lin and Jeng, 2006; Colombo et al., 2006; Giret and Botti, 2006; Lastra and Colombo, 2006; Simao et al., 2006; Younus et al., 2009). However, each approach focuses on a certain industry sector describing specific functionality using own notations. There is need for one standard open framework, describing diverse functionality with a common notation. Some MES developers actually use ISA 95 as underlying data model for their MES solution (Blekkink, 2008). The standard defines the basic structure for the creation of the different MES activities such as a 95-scheduler (Scholten, 2005), 95-tracer, 95-documenter, etc. In combination with the upcoming guidelines for MOM transactions (ISA 95 part 6), a Service Oriented Architecture (SOA) could regulate the information exchange within MOM, whereas now it is only used to connect MOM with other business systems such as ERP, Supply Chain Management (SCM), Customer Relationship Management (CRM), Product Lifecycle Management (PLM), etc. by using B2MML. After Point-to-Point (P2P) and Enterprise Application Integration (EAI), Service Oriented Architecture (SOA) is the current leading architecture for distributed systems (MESA International, 2008b). SOA, used in combination with appropriate industry standards and Continuous Improvement (CI) methods, allows for a plug-and-play type of architecture for IT systems. In essence, the IT system's functionality can be added, changed or removed quickly as market demands require business changes. With SOA, the idea is that business drives the IT systems, rather than the IT systems dictating how the business runs. Besides an Enterprise Services Bus (ESB), the manufacturing 2.0 architecture approach highlights the requirement for a separate Manufacturing Services Bus (MSB) to enable communication within MOM (MESA International, 2010b). This is due to the high number of transactions, high parametric data load and near-real-time requirements of simultaneous MOM activities of work flows for production, maintenance, quality, and inventory movement. This complex architectural problem is often underestimated and is then further complicated by frequent changes. The MSB is typically scaled down to a plant site or area of a plant or across multiple production facilities depending on the transaction/data load and response requirements of the operations work flows being supported by the plant applications. The manufacturing SOA is part of the enterprise SOA (Figure 2.5). A key aspect of the Mfg 2.0 architecture is the manufacturing Master Data Management (mMDM) which is differentiated from Master Data Management (MDM) on the ESB for the enterprise business processes. mMDM services a different set of execution applications for manufacturing operations management such as dispatching, route execution, and alarm & event applications. These applications have a more granular set of objects, attributes and production rules than MDM which represents enterprise planning, master scheduling and logistics. The Operations Data Store (ODS) provides a common data platform and enables the integration and analysis of process data. Recent literature (Saenz de Ugarte et al., 2009; Meyer, 2010) tackles the current MES architecture, models and technologies and discusses future trends and challenges.

## 2.2 Lean thinking

### 2.2.1 The Lean philosophy

Today's economic environment drives the adoption of strategic initiatives. In order to survive, companies need to get the most and the best out of the available resources. It is a continuous struggle to eliminate unnecessary production costs; improve manufacturing, process and business performance; increase throughput; reduce cycle times; maintain quality; etc. (Epicor, 2008a). One of the strategic initiatives that helps manufacturers to remain competitive is Lean Manufacturing. Lean is a philosophy carrying the motto 'Doing more, with less!'. The concept of 'Lean' was first introduced by Womack et al. (1990) in order to describe the working philosophy and practices of the Japanese vehicle manufacturers and in particular the Toyota Production System (TPS). The essence of Lean thinking is specifying value and - by doing so - simultaneously uncovering waste. The initial concept of Lean was extended to five key principles by Womack and Jones (1996):

1. **Specify value** - Define value precisely from the perspective of the end customer in terms of the specific product with specific capabilities offered at a specific time.

2. **Identify value streams** - Identify the entire value stream for each product and eliminate waste.

3. **Make value flow** - Make the remaining value steps flow.

4. **Let the customer pull value** - Design and provide what the customer wants only when the customer wants it.

5. **Pursue perfection** - Strive for perfection by continually removing successive layers of waste as they are uncovered.

The ultimate goal is a production process without any of the seven deadly wastes: overproduction, waiting, transport, extra processing, inventory, motion and defects. However, as that situation is impossible to reach, Lean manufacturing is a continuous process toward perfection.

The relative success of Lean Manufacturing resulted in an application of the Lean philosophy beyond the primary manufacturing system. For example, Poppendieck and Poppendieck (2003) applied the lean philosophy to the software development process to obtain quality improvements. Salem et al. (2006) proposes the use of lean thinking in the construction industry. Hicks (2007) discusses the application of lean thinking to information management. Information management considers adding value to information by the way it is organized, visualized and represented and enabling information (value) to flow to the end-user (customer) through the processes of exchange, sharing and collaboration. These are only a few examples of the various implementation domains of Lean Thinking over the past years.

### 2.2.2 Lean tools and techniques

Lean thinking has evolved over time and has expanded beyond its origins in the automotive industry and its narrow definition around shop floor improvement (Hines et al., 2004). Lean is a philosophy and not a tool itself. Numerous tools and techniques - such as Single Minute Exchange of Dies (SMED), Six Sigma ($6\sigma$), Kanban, Value Stream Mapping (VSM), workplace organization (5S), TQM, Theory of Constraints (ToC), Total Productive Maintenance (TPM), Business Process Management (BPM), Visual Management, etc. - can support the Lean transformation in order to identify, measure and remove waste, variability and overburden and deliver improvements in specific areas. SMED reduces waiting and overproduction by creating shorter machine setup times. VSM draws the actual material (and information) flow through the manufacturing process and can reveal important areas for improvement. VSM can be considered as the starting point for any Lean transformation and its applicability is well documented in literature (Rother and Shook, 1999; Braglia et al., 2006; Abdulmalek and Rajgopal, 2007; Nash and Poling, 2008; Mazur and Chen, 2008; Serrano et al., 2008). Kanban reduces inventory by introducing a customer pulled production system. The thoughtful application of the various approaches to exploit full Lean potential has had its share of attention (Shah and Ward, 2003; Lasa et al., 2009). In order to avoid the misapplication of Lean manufacturing tools and metrics, Pavnaskar et al. (2003) introduce a classification scheme. With the classification scheme, manufacturing problems can be linked to the appropriate Lean manufacturing tools that will solve the problem.

A Lean journey typically starts on a higher level by drawing and analyzing the value stream map. VSM maps not only the material flows but also the information flows that signal and control the flow of materials. The material flow path of each finished product is traced back from its final operation (delivery to customer) to its first (reception of raw materials). By means of this visual representation, value-adding steps can be identified and wasteful activities eliminated. VSM is based on five phases put into practice by a special team created for such a purpose (Rother and Shook, 1999): (1) selection of a product family; (2) current state mapping; (3) future state mapping; (4) defining a work plan; (5) achieving the work plan. Similarities between product work flows are searched for to define product families. The necessary data are collected by walking through the production process. The current state map is drawn with paper and pencil based on standard VSM icons and conventions. After analysis, a future state map and a Lean transformation plan is created. A number of kaizen[7] events determine the required actions (e.g. introduce pull system, increase operator efficiency, reduce changeover time or re-layout the factory floor) to reach the desired future state. This VSM approach works well for high-volume environments like automotive. However, as Lean (and VSM) has evolved over time and has expanded beyond its origins in the automotive industry (Hines et al., 2004), some

[7] Japanese for 'improvement' or 'change for the better'. It refers to the philosophy or practices that focus upon CI of processes in manufacturing, engineering and business management. There is one significant difference between kaizen and innovation: Kaizen does not necessarily call for a large investment in capital to implement the strategy (Terziovski and Sohal, 2000).

situations are too complex or too elaborate to be performed by the original approach. Some extensions to traditional VSM are developed. When high-mix environments have thousands of products passing through dozens of work centers using a variety of possible routings, a more general approach to defining value streams is required (MESA International, 2010a). Flow paths group products that visit similar work centers (Duggan, 2002). Multiple flow paths can be defined for a plant, but a product can belong to only one flow path. Lean optimizes the flow of materials through each flow path, maximizing throughput and customer service while minimizing inventory and cycle time. Despite success stories in the application of VSM, variants of the original technique emerged as a result of applications in different environments and contexts. Value Network Mapping (VNM) was developed to eliminate the limitations imposed on the traditional methodology when many value streams have multiple flows that merge (Khaswala and Irani, 2001). VNM is able to map the complete network of the flows in a value chain that belongs to a complex product, with complex bill of material and several levels of assembly. Also, it utilizes algorithms for clustering of similar manufacturing routings and design of facility layouts to identify families of similar routings for which a single composite current state map could be developed. In addition, these algorithms utilize special data structures that capture the complete assembly structure of the product instead of extracting the key components only, as suggested to be done with VSM.

An example of a current state map is depicted in figure 2.7. The value stream of the product family 'final boxes'[8] is drawn for a fictitious company CharBox. Average demand is 117 boxes a day. The map is documented with some typical facts. At each process (indicated by a rectangle) the cycle time C/T, the change-over time C/O, the uptime U/T and the traveled distance is measured and added as information to the map. Inside the process box, also the number of operators - present at the time of analysis - is noted down. At each inventory location (indicated by a triangle) the number of components is counted and the distance a product travels in between two processes is noted down. A timeline is constructed for the complete material flow. Inventory is converted to its time value based on customer demand and adjusted considering the uptime of the subsequent process. The Product Lead Time (PLT) is the total time a product is present in the value stream, from arrival of raw materials till delivery to the customer. It is the sum of all cycle times and inventory waiting times. The Total Completion Time (TCT) is the total time the product is actually being processed and is the sum of all cycle times. The ratio value-added time ($\leq$ TCT) to total time (PLT) in this case is less than $0.144\%$. That means that during less than $0.144\%$ of the time the product is present on the production floor, value is being added. Also the information flow is depicted. It is a typical case of push flow. All processes are centrally controlled based on customer orders and inventory records. The customers give monthly forecasts and weekly orders. Based on this input, Manufacturing Resource Planning (MRP II) generates raw material requirements and a production schedule. Raw material requirements are send to the supplier through monthly forecasts and weekly or-

[8]The final products consist of box type A or box type B, containing a certain number of characters (40 types). There is only one type of raw material (standard sheet) that can be cut into 3 different formats (A - B - Char).

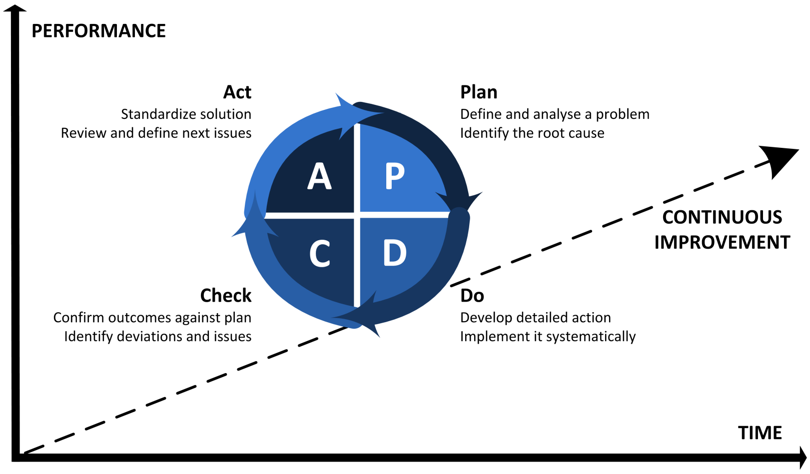



*Figure 2.6: The different stages in Deming's PDCA cycle*

ders. The supplier delivers once a week. Two times a day, transport occurs to customers. A production manager generates daily schedules for all processes, based on the weekly production schedule from ERP. He manually follows up production progress to determine and update the daily schedules.

The Lean transformation plan consists of a number of improvement events. They are visualized on the future state map through kaizen bursts (Figure 2.8). The CI concept is driven by Deming's Cycle (Deming, 1986). This methodology consists of four stages: Plan-Do-Check-Act (PDCA) (Figure 2.6). The Plan stage consists of studying the current situation, gathering data and planning for improvement. In the Do stage, the plan is implemented on a trial basis. The Check stage is designed to determine if the trial plan is working correctly and if any further problems or opportunities are found. The last stage, Act, is the implementation of the final plan to ensure that the improvements will be standardized and practiced continuously. This leads back to the Plan stage for further diagnosis and improvement. Consider the introduction of a pull system as an example of a Lean transformation step. In a pull system, processes are not centrally controlled, but triggered by the first process downstream. A production process is only active when there is demand. For final products, production is determined by customer demand. Internal processes handle requests of their subsequent process. Kanban cards are a popular way to control the operation of a pull system. Toyota's Ohno (1988) introduced kanban as a tool in the development of JIT manufacturing. These cards limit inventory levels in between processes. Roughly said, a process may only produce when it possesses a free kanban card. The production rhythm or takt time is determined by customer demand. For the CharBox case, equation 2.1 gives a takt time of 4.1 minutes. That means that each process has 4.1 minutes to add value to one unit. The pacemaker is the process where the flow stops and pull begins. For pure pull system value streams, the pacemaker should be placed as close to the very end of the process flow as possible. In customized production settings, the pacemaker is often found much more upstream, usually the last point of commonality, which is the *assembly* process for the CharBox case. Operation is controlled by a daily schedule from production control. By First In - First Out (FIFO) lanes, downstream processes are streamlined, limiting inventory to maximum 20 boxes in this case. Packaging and Shipping is grouped together to approach the takt time. One operator is made available to guide the Lean journey.

$$\text{T} = \frac{T_a}{T_d} = \frac{8 * 60}{117} = 4.1 \text{ minutes} \tag{2.1}$$

with

$T$ = Takt time

$T_a$ = Net time available to work (leave out breaks!), e.g. [minutes / day]

$T_d$ = Average daily demand, e.g. [units required / day]

In front of the pacemaker, uncertainty is handled by different kanban loops. Container quantities are set to 10% of daily demand[9]. The amount of cards can be determined by equation 2.2 (Co and Sharafali, 1997). The lead time of a kanban request is the sum of the total processing time of the container at the upstream process and the total waiting time[10] of the kanban request.

$$n = \frac{d_{av}.(t_w + t_{pc})s}{k} \tag{2.2}$$

with

$n$ = Number of kanban cards

$d_{av}$ = Average daily demand

$t_w$ = Waiting time per container

$t_{pc}$ = Processing time per container

$k$ = Container quantity

$s$ = Safety factor

Figure 2.8 shows an example of a future state map. The ratio value-added time of the new value stream can be improved to 1.86%. Following up the Lean progress is done by continuously repeating the data collection and drawing steps.

[9] A good rule of thumb, limiting the number of setups to ten setups per day for each part.

[10] As well the time from kanban request to the start of processing as the time needed to bring the container to the supermarket after processing.

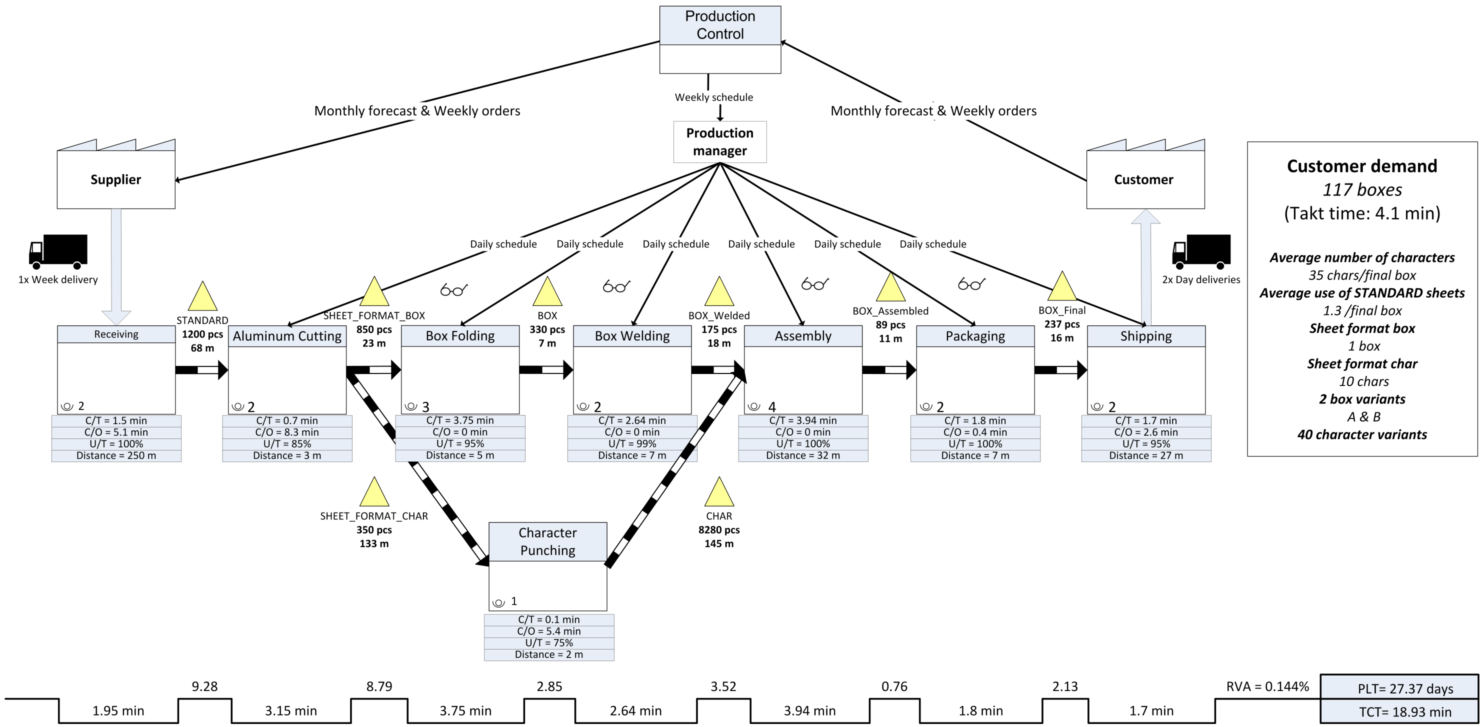



*Figure 2.7: A current state map example representing the material and information flow of the product family 'final boxes' of the CharBox company*

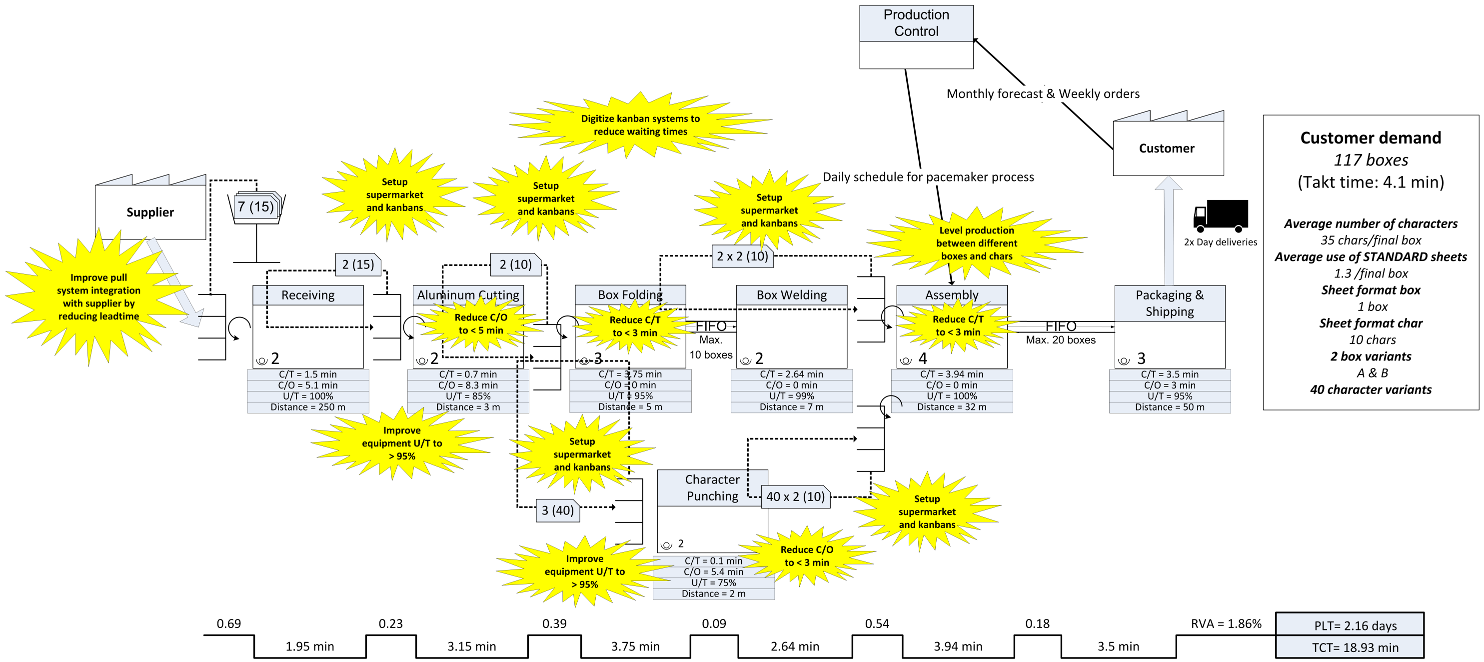



*Figure 2.8: A future state map example representing the material and information flow of the product family 'final boxes' of the CharBox company*

### 2.2.3 Lean metrics and assessment

As various tools and techniques exist to work towards the Lean goal, it is necessary to carefully plan and keep track of the Lean efforts. VSM results in the construction of a Lean roadmap. This work plan is a sequence of Lean practices that will be performed in order to evolve from the current (AS-IS) to the future (TO-BE) situation. A Lean planning system can document as well the progress as the impact of each step on carefully selected Lean metrics. This assessment tool structures the Lean journey by continuously updating the performance and the work plan. Lean metrics are a set of performance measures for Lean manufacturing. Examples are process throughput, total manufacturing lead time, labor productivity, OEE, etc. Many studies define their own metrics by performing some sort of statistical analysis on survey data. Shah and Ward (2007) use a feature extraction method to determine adequate measures of Lean production. Ray et al. (2006) developed a Lean index for the wood products industry. The study demonstrates that the statistical methodology of factor analysis can be used to develop a quantitative definition and assessment of the concept of 'leanness' for any wood processing company. The impact of typical Lean activities on the features of a Lean environment and the Lean performance metrics are presented by Duque and Cadavid (2007). Mejabi (2003) proposes a framework for a Lean planning system that can be used to monitor and quantify the continuous improvement efforts. By following up meaningful Lean metrics, the progress can be assessed. It is key to keep the CI ball going towards perfection (Figure 2.6).

## 2.3 Lean & IT

Originally, Lean practices were considered to be based on purely manual efforts. The project team starts from scratch and analyses the current situation by walking through the production process (Biddle, 2006). The application of IT and Lean principles have long been seen as mutually exclusive. Lean advocates have the idea of putting in place a simplified information management system (Houy, 2005). They consider that organizations based on continuous flow should limit information needs to local communication between upstream and downstream production units. In their view, it is preferable for employees to search for the information they need, as and when they need it, rather than configuring software to provide them with information that is repeated at predetermined times. Womack (2004) gives the following idea about information management:

> *Piling up information in a large inventory is as bad - maybe worse - than piling up large inventories of products.*

Information must be sent in small batches at a high frequency instead of large batches infrequently. System failures must be made immediately visible, so that they can be treated directly. Manual systems - such as the labeling system (Kanban), the andon cord and others - are more suitable because they are harder to ignore and force immediate action. Lean purists maintain it is preferable to eliminate the causes of malfunctioning than to automate reporting functions aimed at warning managers of the existence of the problem.

However, Lean and IT are more and more claimed to be interdependent and complementary (Epicor, 2008b; Riezebos et al., 2009). Within literature, Lean IT can mean one of two things. Either it is a Lean look at IT or software support for Lean practices.

### 2.3.1 Lean look at IT

The emergence of new technologies (e.g. SOA) make it more and more possible to apply to the decentralized information needs stated by Lean practitioners (Pfadenhauer et al., 2006; MESA International, 2008b). Hicks (2007) discusses the application of Lean Thinking on information management. The seven deadly wastes are projected on the use of IT systems (Table 2.1). The product flow in Lean Manufacturing is replaced by a flow of information. All information is pulled by the customer. That can be another system or a person. When a manager requests a KPI, then he is the customer. The information must flow to the customer as fast as possible. Figure 2.9 shows some basic steps in the value stream of the information. There are three basic states: Data, information and value. However, each state can occur multiple times in one particular value stream. Data are raw bits and bytes, with no immediate information value. A bit that is logged to indicate if a machine was running at each second can be considered raw data. These data can be processed to some kind of useful information. If the data of the running machine is collected during one week, the downtime during that week can be calculated (for example 5% downtime that week). Based on that information, a decision can be made. If the downtime is very high, the cause can be examined and corrected (e.g. schedule preventive maintenance, introduce TPM, etc.). The result of this decision making is the crucial value of the information flow. The goal is flowing as fast as possible from data collection to value by means of pull signals. Suppose the manager wants to know what the Overall Equipment Effectivenss (OEE) is of one of his machines this month. Equation 2.3 shows the information needs in order to construct the value. It requests the availability (inactivity losses), the performance (speed losses) and the quality (defect losses) information of the equipment (e.g. during the last month). To get each of those, a bunch of data is requested to or measured by the data collection system. Then the information value stream starts. The collected data are processed. The information is constructed and finally the requested OEE value is presented to the manager to start decision making and generate value by taking appropriate action. Every information flow must start with the idea of creating value. Just like any material flow starts with the idea of creating a final product for the customer. The human role in decision making is crucial. But, providing him with the right information, at the right time, at the right place, in the right format can boost the efficiency, quality and impact of the decisions.

$$
\begin{aligned}
OEE &= \text{100 x Availability x Performance x Quality} \qquad (2.3)\\
&= 100.\frac{T_r}{T_a}.\frac{E_s}{E_c}.\frac{P_g}{P_t}
\end{aligned}
$$

with

$$
\begin{aligned}
T_a &= \text{Equipment time available}\\
T_r &= \text{Equipment actual run time}\\
E_c &= \text{Equipment maximum capability}\\
E_s &= \text{Equipment actual speed}\\
P_t &= \text{Total number of parts produced}\\
P_g &= \text{Number of good parts produced}
\end{aligned}
$$

In the same way, Lean can be applied to the software development domain (Poppendieck and Poppendieck, 2003; Dasari, 2005). Lean software development helps software organizations optimize their processes and production methods in order to deliver their products to the market much faster and with better quality. It can be considered as a new development method that tries to identify all problems of old methodologies like the waterfall model. Lean puts the main focus on people and communication. If people who produce the software are respected and they communicate efficiently, it is more likely that they will deliver a good product and the final customer will be satisfied.

| Waste | Description |
|---|---|
| **Overproduction** | Producing reports or information that the customer will not use, or does not need. |
| **Waiting** | Forcing the customer to wait for information to support actions or decisions. Or not providing all the necessary information. |
| **Transport** | Moving data from one system to another because they have different underlying data models. |
| **Extra Processing** | Duplicate data entry and maintenance. |
| **Inventory** | Storing unnecessary data. |
| **Motion** | Providing data in the wrong format or at the wrong time. |
| **Defects** | Incorrect data or too much checking for change. |

*Table 2.1: The seven deadly wastes defined by Lean information management (Based on Waterhouse (2008))*

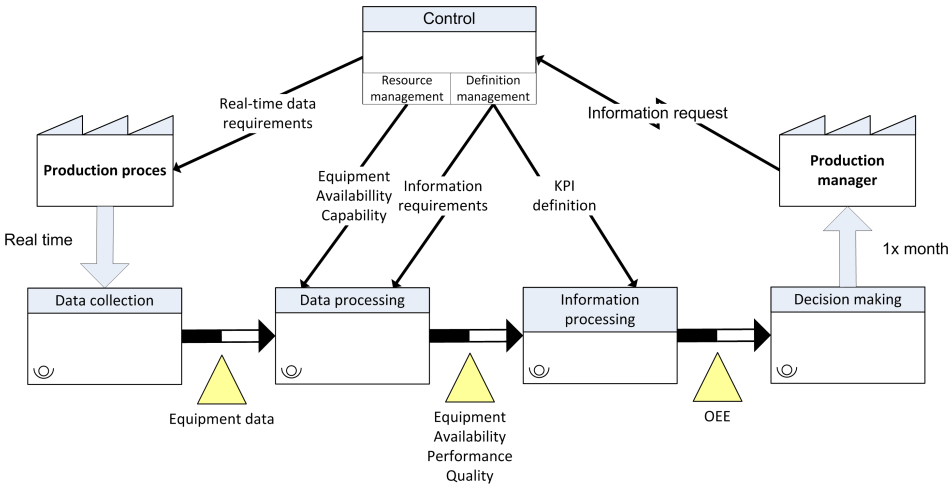



*Figure 2.9: The information value stream to determine OEE*

### 2.3.2 Software support for Lean

A Lean approach to high product mix, shared production assets and volatile demand scenarios is far from evident. Kanban cards and heijunka boards become unmanageable. Calculating raw material, work in process, finished goods inventories, etc. can no longer be based on simple rules of thumb and experimental design. This is where IT comes in handy. Complex issues can easily be dealt with in real-time. For example, Wan and Chen (2007) describe a web-based kanban system for job dispatching, tracking and performance monitoring. Lean IT solutions can also connect with suppliers, for example to include them in kanban loops. The legal provisions in regulated industries (ex. food, pharmaceutical) require tracing functionality to link each finished product to its raw materials and processing steps. Without IT support, this task would be impossible to achieve. Another issue is maintaining the achieved improvements. The human factor plays a crucial role when it comes to process improvements. But it is also very important to maintain those accomplished improvements. IT is seen as an enabler of the implemented improvements. IT can even structure and follow up the CI progress. Bell (2005) and Rio (2005) describe IT as the ideal solution to enforce standard work procedures. IT can be used to transform the codified knowledge of operators into collective knowledge. New technologies facilitate the sharing of codified knowledge between the company's employees (Houy, 2005). Ward and Zhou (2006) concluded that IT integration facilitates the implementation and the use of effective Lean/JIT practices. A number of Lean tools and techniques already benefit from software support:

- Some possible limitations of a purely manual VSM approach are:
  - It is time and labor consuming. It takes a while to walk through the whole process and collect all necessary data.
  - The result is only a snapshot of the real value stream and can lead to poor decisions.
  - Additional data must be collected when performing a root cause analysis. There is no possibility to dynamically drill down into the data.
  - The manual process is prone to different kinds of errors: process interpretation faults, wrong measurements, writing or reading errors, vague estimates, etc.
  - The manual drawing of the current and future state can be sloppy and cause misinterpretation within the team.
  - The operational threshold is very high. The data collection will not be done frequently due to the high labor intensity. That can cause an inefficient follow-up of the progress and - as a consequence - an inability to react to changing circumstances. An insufficient follow-up makes it hard to sustain the continuous improvement initiatives.

  The use of IT can increase the practical performance of VSM (Serrano et al., 2008). There are electronic tools available that allow a better representation of the maps, support the analysis and document and visualize the progress. They are called electronic Value Stream Mapping (eVSM) tools and are mostly based on spreadsheets. Another recent evolution is the combination of VSM with Discrete Event Simulation (DES) to analyze and evaluate the current and future states (Lian and Van Landeghem, 2007). After a simulation run, the potential impact of the proposed modifications can be measured. This allows the team to make changes and observe the effects without disrupting the production process or causing downtime and costs. But the main effort, collecting the data, remains currently purely manual. Through automated data collection, the current material flow and process performance can be generated in real-time. As this information is available in many cases anyway, it can partly eliminate the time consuming and error prone manual data collection and entry. At least, it could be used to validate the manual efforts. In addition, it supports the CI process by lowering the operational threshold and enabling an effective follow up.

- The electronic Kanban (eKanban) system offers considerable benefits compared to the original manual configuration. No cards can be lost. Barcodes or even Radio Frequency Identification (RFID) tags make them easier to track in real-time and trace through history records. The software allows an easier reconfiguration of the kanban system through automatic kanban sizing. Finally eKanban makes it more efficient to integrate with suppliers.

- Visual Management must make it possible that anyone entering the workplace, even those who are unfamiliar with the detail of the processes, can rapidly see what is going on, understand it and see what is under control and what is not. Essentially, the current status of the operation can be assessed, at a glance. Automatically generated KPI, alarm events and other graphical reports presented to the operator in real-time can outperform manual systems.

Some research has already been done on the combination between the Lean Production System and ERP (Goddard, 2003; Sandras, 2003; Bell, 2005). But the entrance of MES brings new insights to the Lean IT subject. The (near) real-time information capabilities of MES look like a better fit for Lean than the batch oriented ERP systems. No previous research on this topic has been found, but software vendors already anticipate the Lean MES story. However, a study of AMR (Masson and Jacobson, 2007) shows a limited adoption of Lean IT so far. Ease of deployment and use remains a barrier to the adoption of Lean software on the shop floor. There is still room for innovators, for example to provide much-needed analytical workbenches on top of real-time data collection. A functionality that - as tackled in the next section - can be aligned with MES and is part of the presented framework. ISA 95 is seen as a standard framework for every MES application. So it is the obvious framework to start the study from. In the next section, the interrelationship between MES and CI will be further investigated.

## 2.4 The role of MES in CI

ERP's inability to efficiently manage shop floor processes, resulted in the emergence of MES. Academic literature on the combination of the Lean production system and ERP is scarce and - based on the same inability - does not exactly encourage a combined approach (Goddard, 2003). However, a modified look at ERP can deliver a match for Lean (Sandras, 2003; Bell, 2005). As Lean (tools and techniques) and MES both operate the MOM layer, finding a match between them seems more likely. New technologies - such as SOA - enable the development of software systems that are able to support the requirements of Lean information management (Pfadenhauer et al., 2006). These MES solutions can be flexible enough to accommodate the Continuous Improvement (CI) philosophy of a Lean environment. The (near) real-time information flow of the MES looks like a better fit for Lean than the batch oriented ERP systems. Although this issue has been acknowledged by practitioners for some years now (Gifford, 2002; Fraser and Greene, 2005; MESA International, 2008a), academic literature still lacks attention to the subject (Saenz de Ugarte et al., 2009). Stand-alone applications that automate and support Lean practices are already available on the market, such as eKanban, Six Sigma programs, Visual Management screens, KPI dashboards, etc. More and more MES software vendors have some Lean support incorporated. Every product folder has some reference to the Lean philosophy (Wonderware, 2006; Siemens IT Solutions, 2007; MESware, 2008; GE Fanuc Intelligent Platforms, 2009). It must be that there is a need for an MES that fully supports the Lean philosophy.

Before implementing an MES, all processes - as well from the material as the information flow - must be critically reviewed to ensure an optimal work flow. Lean practitioners strongly suggest a manual Lean transformation before IT adoption (Masson and Jacobson, 2007). But at which point can you switch from manual to IT? When your processes are perfect and will not change anymore? Lean is a CI process, so that situation will never occur. In addition, even early Lean efforts can benefit from IT support, in particular for data collection and analysis. Some functionalities even require the support of IT, because they are too complex (e.g. controlling WIP with high product mix and volatile demand) or simply enforced by legal provisions (e.g. tracking & tracing in the food industry). So why not take both Lean and MES into account during the first analysis and take the best of both (Gifford, 2002)? This approach could also have a positive impact on the investment analysis, as the intangible benefits of IT are quite difficult to quantify (Nagalingam and Lin, 1997; Nasarwanji et al., 2009; Fraser, 2009). The quick wins of the Lean transformation could help justify the initial investment cost of MES.

### 2.4.1 Manufacturing Intelligence (MI)

In its Plant-to-Enterprise (P2E) model (Figure 2.10), the MESA shows how strategic initiatives are linked to the shop floor within the entire enterprise IT system (MESA International, 2008a). The model depicts the generation of information at the most basic value adding process levels of the plant and how this information supports and is supported by

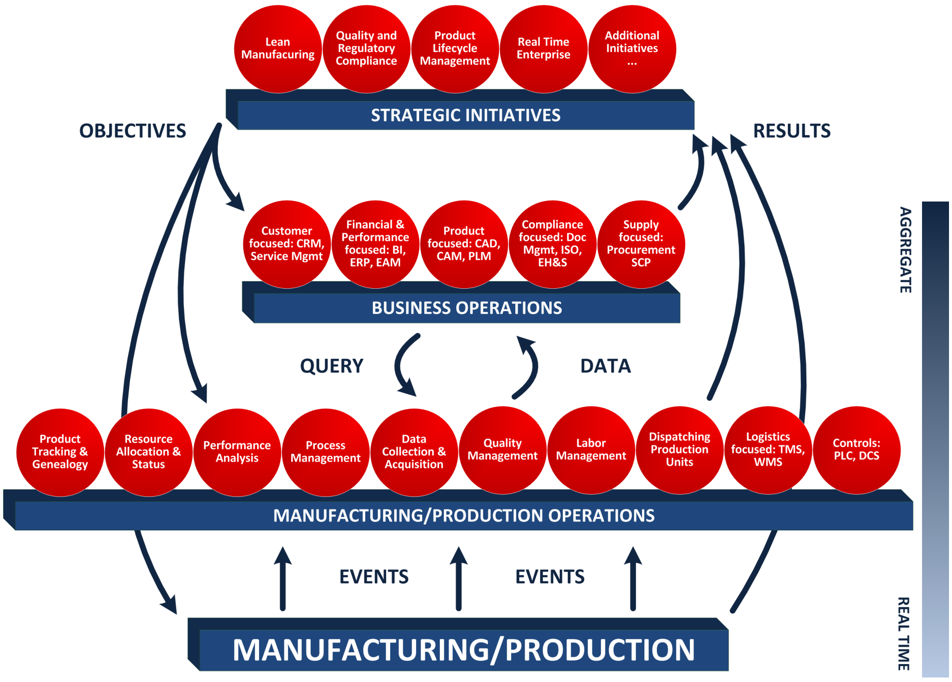



*Figure 2.10: Plant-to-Enterprise model of MESA (MESA International, 2008a)*

enterprise business application processes and longer term strategic initiatives. The importance of a well established MOM layer to create the necessary real-time manufacturing visibility is emphasized. MESA published manufacturing guidebooks for each strategic initiative they defined. Lean manufacturing is one of them (MESA International, 2010a).

Collecting, maintaining and updating the business data in support of the business processes, is important for daily operations. But additionally, in-depth business visibility can be created by adding an appropriate level of intelligence. Carefully designed windows on the data can extract useful information, that is not visible at first sight. This Business Intelligence (BI) can expose the necessary opportunities to steer the business decision-making process. Figure 2.11 shows how this idea can be extended to the manufacturing level. Real-time production information is crucial to the daily manufacturing operations. But additionally, Manufacturing Intelligence (MI) can provide the necessary visibility for the continuous improvement efforts within the production facility. The CI philosophy of Lean can be supported by the MI incorporated in MES.

Wigand (2007) refined Leavitt's diamond model of organizations to analyze the impact of Information Technology (with e-mail as IT example) on structure, people and tasks. She concluded that IT efforts are opportunities to capitalize on creating new ways of working by redesigning tasks, changing the roles of individuals, spanning organizational boundaries, creating new communication paths and social interactions and focus-

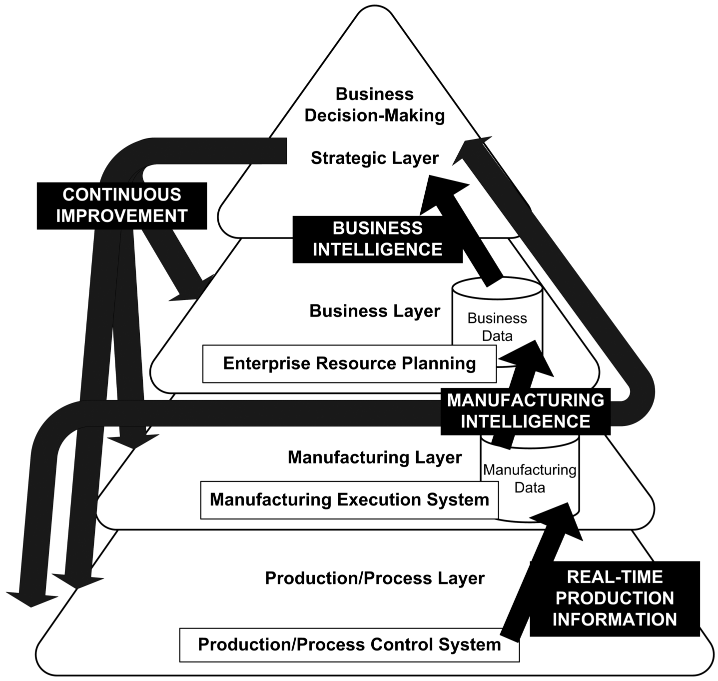



*Figure 2.11: Creating business and manufacturing visibility to support the continuous improvement cycle*

ing on the interactivity of these basic components. This model can also be applied to the use of MOMS in production environments. Automating information flows in the MOM layer, can reveal opportunities to further improve manufacturing operations. Benefits can reach further than the initial goal. The extra visibility can lead to additional value creation (Aberdeen Group, 2005a). An MES, as IT component, interacts with the other basic components of the model:

- **The task to be accomplished** - Software support eliminates wasteful activities, imposes standard work to achieve efficient and qualitative production and gives the opportunity to focus on possible improvements.

- **The role of the individual** - Providing operators with real-time visibility and transparency into production performance, manufacturers can ensure that the right people are able to take the right actions at the right time by adding intelligence to the raw data. Operators get empowered to boost performance.

- **The structure of the organization** - By automating information flows, the different activities within a manufacturing environment (production, maintenance, quality and inventory) can be better synchronized. Software support for planning purposes, can be integrated with maintenance requests. Efficient information flow from

| Nb | Pitfall | Possible role of MES |
|---|---|---|
| 1 | **Lack of clear business goals** | Set and follow up the companies KPIs. Align operational and business metrics. |
| 2 | **Failure to recognize that CI also requires a change management effort** | Give support for standard operational changes and impose the improved way of working. |
| 3 | **Failure to involve factory floor personnel** | Empower operators by providing continuous feedback on their performance based on the critical data they enter. |
| 4 | **Failure to enable real-time visibility and transparency** | Real-time data collection to ensure that the right people are able to take the right actions at the right time. |
| 5 | **Failure to take action** | Inform operators by providing continuous feedback on production performance. Provide everyone with the appropriate tools, so the right people are able to take the right actions at the right time. |
| 6 | **Losing control** | The information made available needs to be relevant, to the point and appropriate to each employee's role. Information overload and application complexity can get everyone caught up in the details and lose sight of what is truly important. Try to avoid over-automation. |
| 7 | **Lack of continued executive sponsorship** | Continuously keep the system up to date, to be able to trigger new improvements. An outdated system loses reliability and credibility and will no longer be used at full potential. |
| 8 | **Deploying inappropriate technology** | Always go for real-time and right information quality, not quantity. Do not select a solution based on the technology itself, but rather the value it can add to MOM. |
| 9 | **Failure to employ a practical and simple implementation** | Technology is just an enabler. Train operators in using continuous improvement methodology and MES itself. Standard tools and techniques can be integrated within MES to provide practical support. |
| 10 | **Take the path of least resistance** | Limit administrative obligations by automating information flows. Make sure the operators only have to input critical information that can not be gathered in another way. |

*Table 2.2: The possible role of MES in avoiding the most common pitfalls of CI (Adjusted from CDC Factory (2007))*

quality testing ensures qualitative production and limited inventory waiting times before product release.

Accordingly, an MES can be an enabler of CI programs. CDC Factory (2007) lists a number of most common causes of CI failure. In order to avoid those pitfalls, an efficient implementation and integration of the MOM layer is crucial. Table 2.2 provides an overview of the role an MES can play in avoiding the different pitfalls. That role defines a number of requirements for the Lean MES.

An MES must incorporate and - even more important - maintain the necessary software support for MOM. In figure 2.12 a stepwise MOM evolution example is given of a small furniture manufacturing company as result of different improvement initiatives. The manufacturing operations performance is given in function of time. The performance

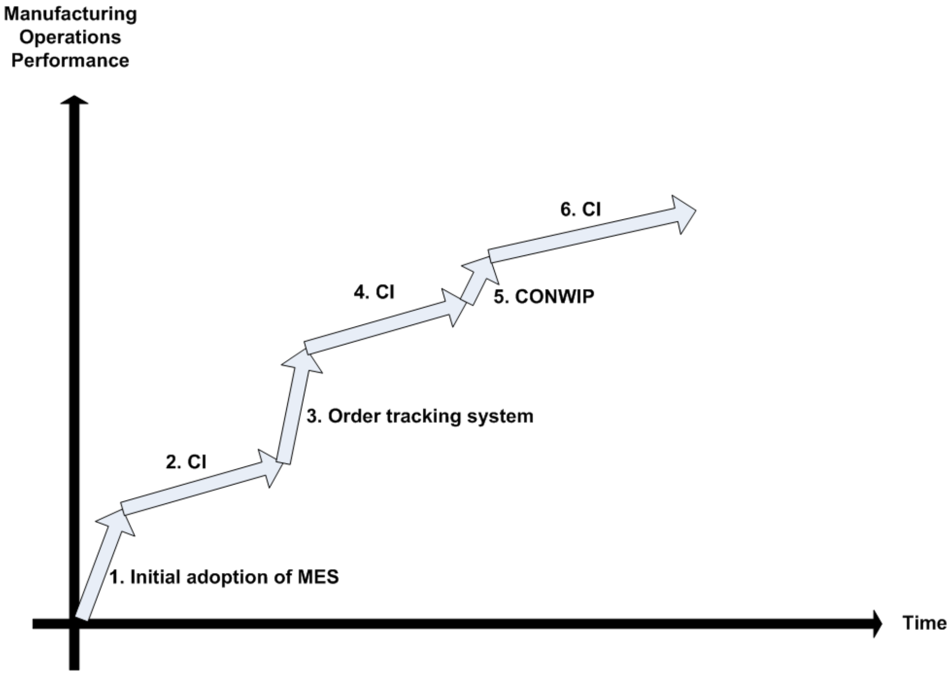



*Figure 2.12: A stepwise evolution example illustrating the influence of different kinds of improvement initiatives on the manufacturing operations performance of a small furniture company*

measure is merely indicative and can be seen as a combination of quality, cost and delivery information. After each MOM innovation step, a continuous improvement initiative uses the extra visibility to fine-tune the new way of working.

1. **Initial adoption of an MES:** Each production activity on an order by an operator is recorded by a barcode scan. The data are necessary to calculate KPIs (number of seats produced, efficiency of employee or work center and leather consumed) and keep track of operator work hours for payment of wages. The support of MES increases the efficiency of the operators (no more manual writing) and the efficiency of administration/manager (no more data collection, entering and structuring in MS Excel).

2. **Continuous improvement:** Based on the historical data available in MES, theoretical production lead times and cost of the different models are gradually fine-tuned. This effort results in a more realistic planning and price setting. An MES functionality is added to monitor the values in the future and provide warnings when theoretical planning and costing parameters deviate systematically.

3. **Order tracking system:** The production manager loses a lot of time distributing

and following up production orders. A paperless system is put in place to track orders on the production floor. Operators use touch panels (instead of barcode scanning) to indicate their production activities. Through the real-time visibility offered by MES, the production manager can now evaluate and manipulate the flow of orders on the production floor from his desk.

4. **Continuous improvement:** Based on his experience, the production manager sets up a priority system for waiting orders at each production step. This system replaces the complex and time consuming planning process in MS Excel. The cutting process combines multiple orders consisting of the same leather type. At the end of the production process, priority is based on the region of the customer to realize an efficient transportation plan. Operators see a sorted list on their touch panel that updates in real-time. Based on ongoing experience, the priority system is further optimized.

5. **Pull system:** In order to reduce the WIP on the production floor (and consequently also the lead time[11]), a pull system is introduced. The production manager uses the order tracking system as Constant Work In Process (CONWIP)[12] system. He only starts a new production order, when an order is finished. At first, the maximum WIP is held fixed on a relatively high level.

6. **Continuous improvement:** The maximum amount of WIP is gradually being reduced and unbalance, bottleneck, quality and other problems come to surface. This can be the breeding ground for future improvements.

This improvement of manufacturing operations has no end, it is a continuous cycle toward perfection. Define-Measure-Analyze-Improve-Control (DMAIC) is a structured and disciplined approach to process improvement and is part of the Six Sigma methodology. It is similar[13] to the PDCA cycle, but adds the important *control* step. Hwang (2006) describes how unsuccessful Six Sigma projects can be avoided by integrating an MES with Six Sigma. The DMAIC methodology is described in detail and - through MES - its measurements are improved for process performance and capability, cycle time, rolled throughput yield and operating costs. Based on DMAIC, the role of MES in process improvement can be illustrated (MESA International, 2010a).

**Define** To implement Lean, company managers first must understand why and where changes are desired and necessary and then determine a clear set of goals that can reflect

[11] Little's Law defines a linear relationship (throughput $\lambda$) between WIP ($L$) and lead time ($W$): $L = \lambda W$

[12] A pull system alternative to kanban that is applicable in high product mix environments (Spearman et al., 1990).

[13] However, there are some important differences. As the word *cycle* suggests, PDCA emphasizes more the need to repeat the steps frequently, while Six Sigma and the DMAIC methodology require a steering committee, tollgates, a champion and a project sponsor. These organizational requirements make DMAIC a lot slower than PDCA which can be organized directly on the shop floor. Lean Six Sigma (George, 2002; Smith, 2003) is a combination of both to achieve as well an improvement in lead time as in statistical control of the production processes. The approach tries to combine the best of both worlds.

improved performance based on Lean concepts. The definition of standard Lean metrics and their data requirements within MES can support this first phase.

**Measure** Management must gather all pertinent data about each core process to understand the company's current performance level. A system that continually wants to improve, relies on feedback. Due to its real-time data availability, MES is seen as the best tool to measure real-time performance indicators such as the use of materials, process times and machine breakdowns (Hwang, 2006; Saenz de Ugarte et al., 2009). Typical operational KPIs reflect safety, customer service and cost factors such as overtime, inventory, utilization and quality (Industry Directions, 2006). One of the best ways to motivate people to improve their performance continuously is to de-emphasize standard accounting measures that focus on cost while increasing the focus on metrics that motivate Lean behavior. Lean implementers should create operational KPIs and then map these directly to the financial metrics. Without such an aligned metric framework, the financial department can not understand how operations must work to achieve optimal performance. One effective way to increase the focus on Lean metrics is to display them in easy-to-understand web pages that provide everyone from shop-floor operators to the CEO with a means to see how well they are performing. Although the technique sounds simple, it can have an enormous positive effect on behavior across the entire company.

**Analyze** The strengths and weaknesses of current processes must be analyzed and specific suggestions for process changes described, along with the need to modify current support systems according to the change. The analysis phase requires human expertise and additional tools such as operational research and analytical methods. Some metrics (e.g. OEE for equipment performance), analysis (e.g. Pareto charts for machine breakdown causes) and custom reporting have become somewhat standard functionality within MES software applications. But the current literature lacks sufficient attention on how to make MES (or even IT in general) support this Lean journey even further (Saenz de Ugarte et al., 2009). Efforts rarely exceed the use of spreadsheets or stand-alone software tools that require intensive human interaction. Many experts in Lean implementation agree that a common reason for failure lies in the tendency to apply the wrong solution to a given problem area (Pavnaskar et al., 2003). A lot of tools and techniques are available, but it is important to select the tool that best applies to the problem at hand. Confusion can also arise as a result of integrating Lean with the existing MES on too many lines at once. Rather than look at a broad spectrum of lines, processes or product types, analyze one at a time. Support for this tool selection and a roadmap for the analysis can be integrated in MES on top of the data collection.

**Improve** The suggestions for improvements are tested through pilot implementations and fully implemented if the desired results are confirmed. During the improvement phase, MES is naturally not involved. Except for the necessary improvement of MES itself to control the improved situation.

**Control** Changes are made to processes and work practices to ensure that the gains made in the improve stage become permanent and will not fade away or be forgotten as people change jobs. To prevent reverting to inefficient habits and methodologies, the inconsistencies and variations that obstruct standard work must be identified and corrected. To succeed in these activities, it is imperative that everyone across the enterprise can see how well they are performing at any given moment in relation to the newly established standards. To control the change, MES can standardize the new way of working by imposing standard work and visualizing actual performance on the shop floor.
As CI opportunities and initiatives are countless, the selection and implementation of the ideal steps during the Lean journey - towards perfection - is no easy task. The same difficulty was encountered in section 2.1 considering the selection and implementation of digital support for MOM. ISA 95 offers a solution by structuring the MOM activities and information flows in order to support the analysis. The standard can even act as underlying data model for an MES solution. Lean and CI activities are also situated within MOM, so why not use ISA 95 to structure both. ISA 95 could form the basis for a Lean MES framework that enables data and analysis support for CI and guides change management to control the achieved improvements.

### 2.4.2 Data & analysis support

Every point of information translation describing key aspects of the manufacturing process becomes a barrier to change. Departmental and organizational boundaries that require a translation of terms and information across various systems introduce errors and require expensive integration that must be maintained. A common data and information model can reduce these sources of error and expense. This canonical schema describes the documents and transactions that support the process flows and mapping of the value stream. Creating such a model is part of the Lean concept of standard work. All systems should speak the same Lean language using a standard work model, signals and information flow from one system to the next. ISA 95 can act as this common information model. Figure 2.13 illustrates the plug-and-play SOA concept of the ISA 95-based integration of an enterprise IT system. If Lean IT functionalities; such as eKanban and eVSM; are implemented with the ability to communicate based on ISA 95, then they can be integrated on-the-fly and exchange information with the other activities within the whole. The content of the enterprise IT system (in between activity bubbles) symbolizes the use of a Manufacturing Services Bus (MSB). The dashed white arrows represent the message-based communication through the MSB to exchange information between the different activities. All activities can swap information within this architecture, but only a subset is shown (the connections that are actually used in this particular situation). By integrating the Lean tools within the enterprise IT system, essential data can be gathered automatically. Driven by the available data, the standard steps of typical Lean tools and techniques can be structured with IT to guide the analysis and support decision making. That way, the right people get the right information and are able to take the right actions at the right time. And due to Lean information management, this can be done more effi-

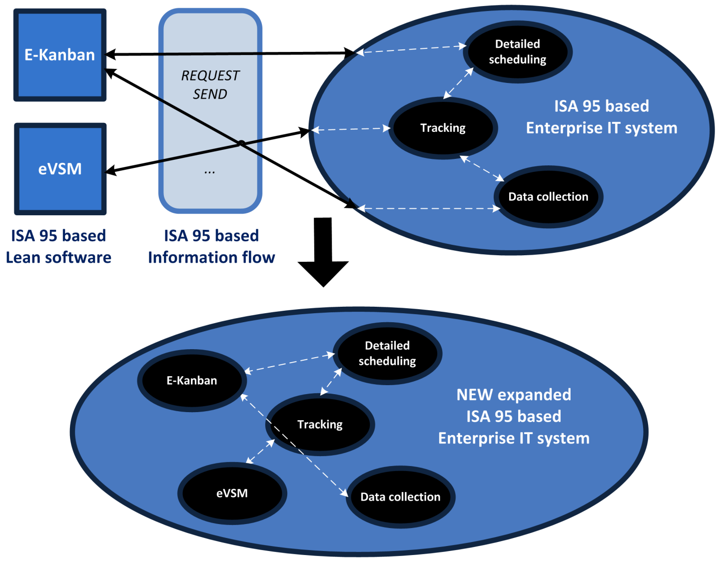



*Figure 2.13: ISA 95 based integration of Lean practices considering the SOA concept*

ciently. The Operations Data Store (ODS) should be the only place within MOM where operations data is maintained. With ISA 95 as common data and information model, all activities - Lean functionality included - can use and adjust the model structure and content during operation. Figure 2.14 illustrates the idea, but does not reflect the architecture. An MSB must enable the communication between all MOM elements. That SOA architecture was introduced in section 2.1.3 and will be discussed in further detail in section 3.2 to structure the Lean MES framework. Using MES data to support the Lean analysis is questioned by Lean purists, as IT can easily be fooled and is considered to be unreliable. However, if that is the case, it seems relevant to get to know how MES is being fooled or why it is obsolete, in order to improve it!

### 2.4.3 Control achieved improvements

The main reason why the use of IT is feared by Lean practitioners is its tendency to become obsolete. Bell (2005) discusses the use of IT to maintain CI initiatives by also adapting the enterprise IT system (In his work: ERP) itself. An MES is located closer to production and is fine-tuned to the specific company needs. The usability of MES highly depends on its ability to reflect the current manufacturing situation. The CI of MES itself during the Lean journey is important to keep the system reliable. Recent literature acknowledges the need for a reconfigurable (Zhaohui et al., 2009) and adaptable (Gang et al., 2010) MES in order to follow manufacturing changes quickly and adequately. An MES should be flexible enough to follow the changes made as result of CI initiatives. People, organizational structure, technology and processes are important pillars of change and


*Figure 2.14: The use of one common ISA 95 based ODS ensures the integration of the MOM activities*

need to interact appropriately to handle its complex nature (Bell, 2005; Wigand, 2007). The MOM framework of ISA 95 (ISA 95, 2000) is believed to be able to structure these change management efforts (MESA International, 2007; Gifford, 2007). This ISA 95 based change management process supports the development of change work flows for on-going operational change and provides a basis for developing a full-scale change management process to facilitate implementing major system and process changes. Not only can ISA 95 guide the change work flow, it can already perform a great deal of the work of standard operational and Lean changes and as a consequence reduce change-over time and possible errors. Through standard ISA 95 model changes, MES can be reconfigured to follow the change and support the new way of working.

## 2.5 Conclusion

This doctoral research combines two manufacturing strategies within one framework: Lean and MES. Each of them contributes to an efficient and qualitative production. To be able to understand further chapters, a general introduction is given on both items and their complementarity.

MOM is responsible for integrating administration with production. It incorporates those activities of a manufacturing facility that coordinate the personnel, equipment, material and energy for the conversion of raw materials into final products. MOM efficiency can be increased by deploying digital information exchange and activity support instead of paper- or spreadsheet-based communication. ISA 95 standardizes the MOM framework and defines four activities: production, maintenance, quality and inventory. It is not stated which system is responsible for each activity, so the actual system can be a customized solution, a combination of integrated subsystems, ERP extensions, dedicated systems (e.g. MES, LES, WMS, MMS and LIMS), etc. However, MES is generally used to describe the complete software system operating the MOM layer. Through digitization and optimization, MOM continuously evolves in order to remain efficient within a changing and demanding manufacturing environment. There is no predefined MOM path to success, each implementation is contingent on a number of factors, making it unique. After P2P and EAI, SOA is the current leading architecture for distributed systems. A description is given of the manufacturing 2.0 architecture that structures an enterprise IT system based on SOA. A discussion on the role of MES in a manufacturing environment has been published in (Cottyn and Capoen, 2009) and (Cottyn and Desmarey, 2010). The practical benefits of the MOM framework of ISA 95 - applied to Small and Medium-sized Enterprises (SME) - is presented in (Desmarey et al., 2011) and (Degryse et al., 2011).

The Lean philosophy is described as a continuous process toward perfection, by removing successive layers of waste. Different Lean tools and techniques can be used to achieve that goal. A popular Lean tool is VSM. The different phases of the analysis are illustrated with an example: (1) selection of a product family; (2) current state mapping; (3) future state mapping; (4) defining a work plan; (5) achieving the work plan. The CI is driven by the PDCA cycle. A Lean planning system can document as well the progress as the impact of each improvement step on Lean metrics.

An overview is given of the complementarity of Lean and IT. Originally, Lean practices were considered to be based on purely manual efforts. However, Lean and IT are more and more claimed to be interdependent and complementary. A distinction is made between a Lean look at IT and software support for Lean practices. Some research has been reported on the combination between Lean and ERP.

Due to ERP's inability to efficiently manage shop floor processes, MES emerged. The main goal of MES is automating activities and information flows in the MOM layer. However, the implementation of MES can reveal opportunities to further improve manufacturing operations. Benefits can reach further than the initial goal. In this chapter the concept of a Lean MES framework was introduced. If an MES is (or will be) implemented, it can facilitate future CI initiatives; such as Lean. A discussion concerning the complementarity of Lean thinking and the ISA 95 standard has been published in (Cottyn et al., 2008). As CI opportunities and initiatives are countless, the selection and implementation of the ideal steps during the Lean journey - towards perfection - is no easy task. MES is believed to be an enabler of CI programs. In order to avoid the most common pitfalls, an efficient implementation and integration of the MOM layer is crucial. An overview was given of the role of an MES in avoiding the different pitfalls. The DMAIC methodology was used to illustrate the role of MES in process improvement. A discussion on the role of MES during a Lean project has been published in (Cottyn et al., 2011c).

# 3

# Lean MES Framework

*This chapter describes the main concept of the thesis, the idea of a Lean MES framework. The framework structures the combination of the optimization and the digitization of MOM. Lean and other CI initiatives continuously try to improve production control. MES supports these PDCA cycles by providing and analyzing historical information. By human efforts, the AS-IS situation is analyzed and TO-BE improvements are introduced. In order to follow up and maintain the new improved situation, MES is modified accordingly. This change management effort keeps MES up to date and imposes standard work on the production floor at all times. Section 3.1 presents an alignment method between MES and Lean. The MES functionalities and Lean practices can be mapped onto the same MOM framework for a specific company situation. The mapping exercise makes it possible to check the necessary information flow in between all components during the MOM analysis. By zooming into a certain functionality, the required information flows can be identified in more detail. To achieve an actual Lean MES integration, this mapping must be automated. Lean functionality must be matched with ISA 95 terminology to enable the standard information exchange. The Lean MES framework structures the necessary components and its contribution is presented in section 3.2. The data and analysis support for VSM, referred to as automated Value Stream Mapping (aVSM), is explored as an example in section 3.3. As part of the activity performance analysis, aVSM can request information or data model changes from the other activities within the Lean MES framework. The requirements to expand the framework with other Lean tools and techniques are discussed. Section 3.4 studies the MES/MOM change management requirements to follow typical Lean MES operational changes. New product introductions, custom reporting and transition to pull production control are described as examples. Section 3.5 lists the main conclusions of this chapter.*

## 3.1 Alignment method

Section 2 illustrated that as well MES as Lean are approaches that have proven their value within manufacturing environments. Both strategies reside in MOM and recent research acknowledges there is a certain overlap between the two. In general, Lean and IT are more and more claimed to be interdependent and complementary. These findings were mainly initiated by practitioners in order to increase the practical performance of both strategies. Currently, in academic research, only the combination of Lean and ERP is briefly discussed from a PPC point of view. There has been little attention to the Lean MES combination so far. However, a number of shortcomings, of both approaches separately, suggest an integration of Lean and MES. Typical problems are: misapplication of Lean tools and techniques, overburden of the operator caused by manual data entry systems, low visibility due to information overload or lack of information, outdated systems that are bypassed or contain wrong data, low operator involvement blocking CI initiatives, recurring to old habits after improvements, complex application of Lean tools and techniques outside their original setting, etc. A Lean MES combination could provide a solution by:

1. **Applying Lean to more complex control issues:** For example, a Lean approach to high product mix, shared production assets and volatile demand scenarios is far from evident. Kanban cards and heijunka boards become unmanageable. Calculating raw material, work in process, finished goods inventories, etc. can no longer be based on simple rules of thumb and experimental design. This is where IT comes in handy. Complex issues can easily be dealt with in real-time. Another example is the integration of suppliers in kanban loops. At first, separate software tools where developed, such as eVSM, eKanban, etc. But as the integration of MOM software tools is currently best practice, why not integrate the Lean functionality in MES?

2. **Making use of the visibility provided by MES for CI selection and execution:** The visibility provided by MES is crucial in order to facilitate operators to see the bigger picture and to anticipate the impact of their decisions. Knowledge about appropriate selection and use of Lean tools and techniques could be integrated. That would contribute to the definition of standard work in a CI context.

3. **Following up Lean progress:** Carefully selected Lean metrics in MES can visualize the impact of the CI initiatives and assess the Lean progress.

4. **Imposing new standard work:** Changes made as result of CI initiatives can be integrated in MES in order to impose the improved way of working on the shop floor.

5. **Maintaining the visibility provided by MES:** An MES should always present the data wished for by the user, at the right format, at the right time, at the right place. The CI of MES itself is important to keep the system reliable. The principles of Lean information management can be applied to achieve that.

Considering the combination of Lean tools and techniques (MOM optimization) and MES production control (MOM digitization), a company approach can be gradually classified into three categories: (1) No alignment; (2) Lean MES alignment; and (3) Lean MES integration. In case of no alignment, there is no interaction between both. Lean practitioners gather information manually and avoid the use of IT, even if digital information is available. MES focuses on push control principles and equipment efficiency (e.g. OEE) and neglects value stream aspects such as lead time reduction, load leveling, etc. Eventually, the standalone application of MES and Lean leads to a mismatch between the production control improvements and systems. As a result, both strategies don't achieve the anticipated long term benefits. A Lean MES alignment seeks opportunities to effectively combine both strategies in a particular case and make them mutually supportive. This is considered to be a one time manual effort. When the alignment is automatically maintained on a regular basis, then a Lean MES integration is achieved. In what follows, ISA 95 is introduced as framework to accomplish Lean MES alignment and integration.

The MOM definition is part of ISA 95 and was mainly introduced to create a common ground to classify and compare existing MES software systems or integrate different Business to Manufacturing (B2M) components to seamlessly one solution. However, MOM provides a framework to classify all manufacturing operations, disregarding the fact whether they are performed manually or automated. Therefore, the framework can also be used to classify the support for Lean practices and, as a consequence, check the possible alignment between MES components and Lean practices. Figure 3.2 illustrates how Lean practices can be mapped onto the same MOM framework for a specific company situation. That makes it possible to check the necessary information flow in between all components during the MOM analysis. By zooming into a certain functionality, the required information flows can be identified in more detail. All information flows consist of standard object models, as defined by ISA 95. Figure 3.1 shows the alignment method for a brown- and greenfield project. Within a brownfield project, historical information is at hand, provided by the current digital MOM support. The information, available within these legacy systems, must be standardized to the ISA 95 format in order to enable a generic MOM analysis. A one-time custom transition can do this job when the current implementation of the MES functionality will most likely be replaced. An ISA 95 plugin may be advisable, when the system remains operational in the future. This effort will continue to facilitate future data analysis and integration projects. A greenfield project can start from scratch. There are no legacy systems that need to be replaced, updated or integrated. The Lean MES analysis starts with a VSM exercise. Historical data can support or validate the manual efforts (e.g. generate an eVSM template). Inefficiencies within the current material and information flow are identified and analyzed. The proposed future state incorporates a number of improvements. A work plan structures the required steps to get from the AS-IS to the TO-BE situation. It is a combination between optimization and digitization steps. The result of the complete exercise is an alignment between MES and the selected Lean practices in the work plan. In a greenfield project, the support is incorporated in the requirements analysis for MES. A change management approach is

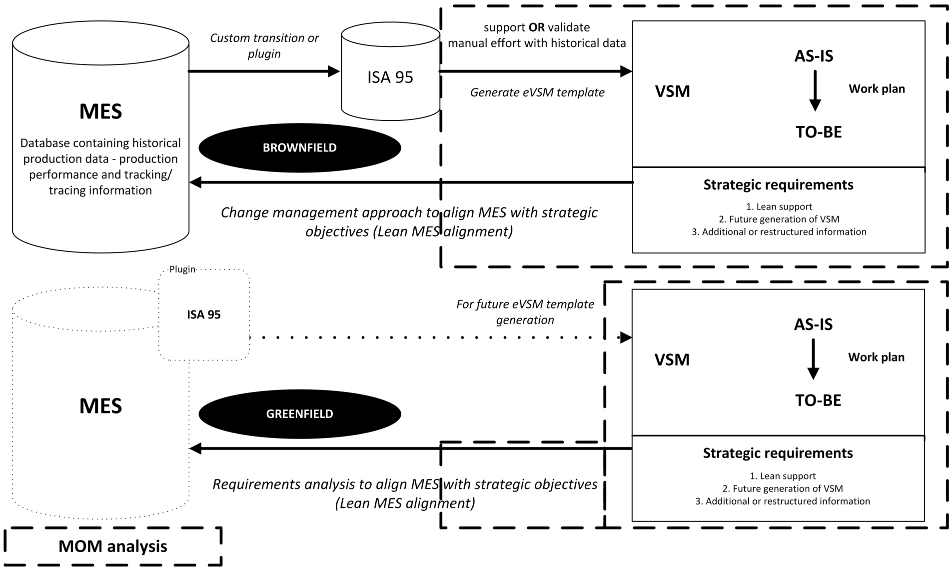



*Figure 3.1: The alignment method for MES and Lean in brown- and greenfield projects based on a generic MOM analysis*

necessary within a brownfield project to restructure MES in order to impose and maintain the new way of working. The alignment of MES with the strategic requirements facilitates the Lean assessment and possible future analyzing efforts. However, as the alignment is a purely manual effort, its efficiency highly depends on the skills and experience of the change team. Therefore, the alignment should be maintained at all times. The role of MES to impose standard work was stated in section 2.4. In support of the CI cycle, the concept of a Lean MES framework is introduced in section 3.2.

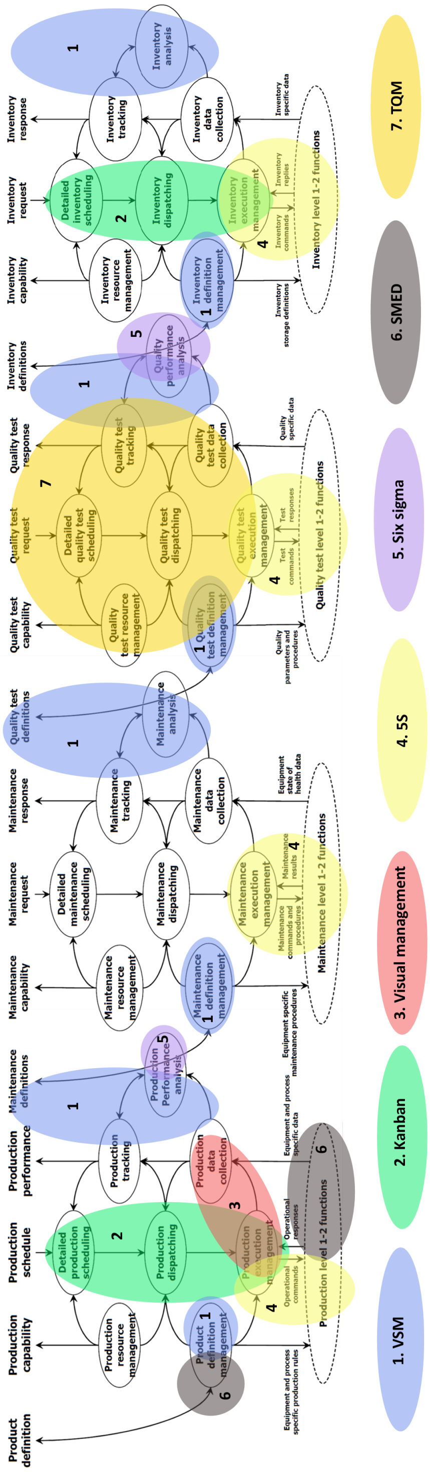



*Figure 3.2: The classification of a number of Lean practices on the MOM framework*

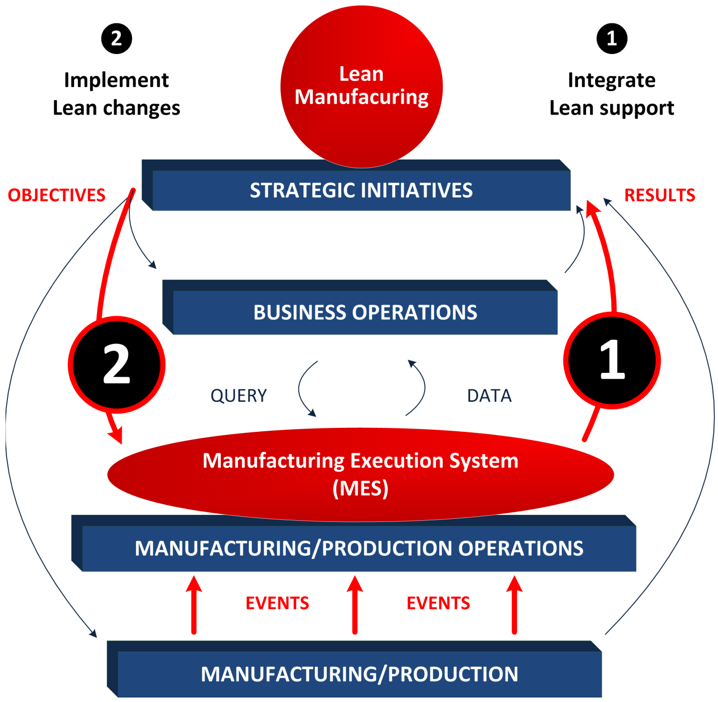



*Figure 3.3: The integration aspects between Lean manufacturing initiatives and a manufacturing execution system operating the manufacturing operations layer (based on the P2E model of MESA (MESA International, 2008a))*

## 3.2 Lean MES framework

The P2E model of MESA was described in section 2.4. Figure 3.3 shows a reduced version of the model, which specifically illustrates the integration between Lean and MES. The Lean MES integration consists of two important aspects:

1. MES must support Lean initiatives with historical operations data and standard tools.

2. The improvements[1] made during the Lean journey must be implemented in MES to keep the system reliable and to impose the improved way of working on the shop floor.

The Lean MES framework defines how the integration of Lean and MES can be initiated and maintained. The manufacturing 2.0 (Mfg 2.0) architecture approach, as discussed in section 2.1.3, is used to structure the different components. Figure 3.4 gives an overview of this SOA integration of MES and Lean activities. Each MOM activity has its specific

[1] Improvements can be typical Lean operational changes, but also MES bug fixes, upgrades or extensions.

task. By applying the message-based communication described in part 5 of ISA 95, information can be exchanged between level 4[2] (connected to ESB) and level 3[3] (connected to MSB) applications using B2MML interfaces. Operations definition management defines all operations-specific information (e.g. how to make the products) and synchronizes that data with level 4 applications. ISA 95 based services enable the communication on the MSB to request actions from other activities. ISA 95 part 6 (currently unpublished) will introduce the standard message-based communication for this information exchange. When operations definition management defines a new final product, a request can be made to operations resource management to manage extra resources, necessary for the production of the new product. The ODS contains all operations data in ISA 95 format. This common data model ensures the integration of all activities. The combination of SOA and the ISA 95 standard allows for a plug-and-play type of architecture for MES. New applications can be connected to the Lean MES by synchronizing with the ODS through the MSB. Due to the high change rate of the Mfg 2.0 applications resulting in new product introductions, changing Stock Keeping Unit (SKU) counts, evolving process technologies and documents and production scaling, mMDM requires a dedicated set of tools and services. This set supports the evolution of activity functionality and interactions in order to keep the production control of MES up to date. To incorporate Lean within the framework, Lean functionality information and standard Lean model transitions are added as extra services to mMDM. This additional information enables the different activities to cooperate as a Lean MES.

Figure 3.3 defined the main components of the Lean MES alignment as data and analysis support and MES/MOM change management. To illustrate the approach, the standard integration of Lean tools will be discussed in the next section. To integrate these concepts within the framework, the Lean functionality must be matched to ISA 95 terminology. Section 3.3 gives an overview of that mapping. As an example, a detailed description is provided for the VSM exercise (i.e. aVSM). In addition, a method to expand the framework with other Lean tools is described. In order to facilitate standard Lean changes within MES, an ISA 95 based change management approach is listed in section 3.4.

The main contribution of the Lean MES framework is a first attempt to formalize the integration of two proven approaches on the shop floor in order to boost their efficiency and effectiveness. However, the impact of the framework can be stated from various points of view.

1. **Research community:** The literature review (chapter 2) indicated some under researched topics in the fields of MES and Lean. Creating and maintaining shop floor visibility is seen as the main goal of an MES. But what the requirements are in order to achieve that visibility and how it can be maintained in a dynamic production environment, still remains an open issue. On the other hand, the value of Lean IT support has been acknowledged in recent literature. But there are still practical

[2]In ISA 95 terminology, level 4 denotes business planning & logistics.
[3]In ISA 95 terminology, level 3 denotes manufacturing operations & control.

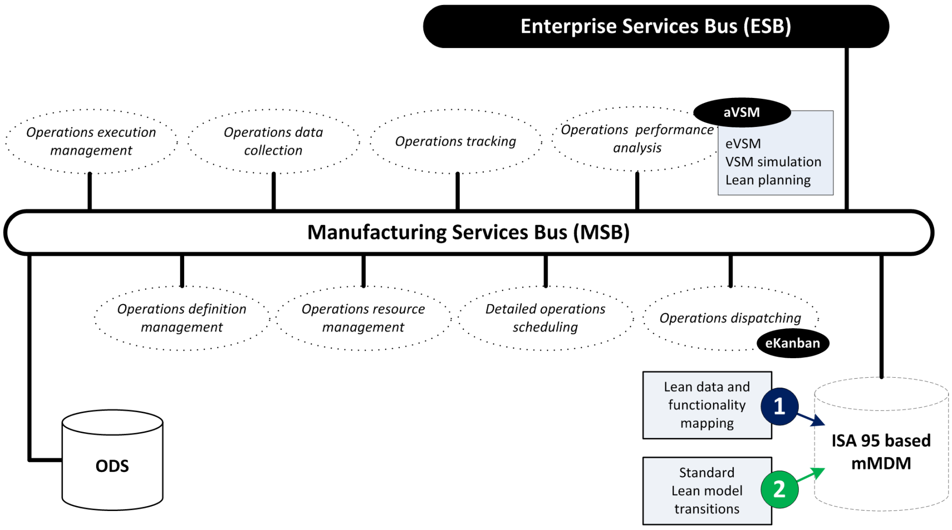



*Figure 3.4: The concept of the Lean MES framework, structured by the Manufacturing 2.0 SOA architecture*

boundaries to the actual use of these systems on the shop floor. The Lean MES framework defines the integration of both proven approaches in order to complement each other. Lean can be used to achieve and maintain MES visibility, while MES boosts the practical performance of Lean. The ISA 95 standard defines a general approach to MES. Lean consists of a standard philosophy; tools and techniques; metrics; etc. to support CI initiatives. The integration is achieved by mapping the two standards within the MOM framework. In chapter 4, the feasibility of the proposed framework will be confirmed. The content and validation of the framework are subject to future research efforts. This research is only the first step towards an integration of Lean and MES.

2. **Standardization organizations:** The MESA community puts a lot of effort in the definition and communication of best practices to achieve operational excellence. They promote a combination of software systems and CI initiatives in order to achieve that goal. Unfortunately, ISA publications in this domain (i.e. ISA 95) focus on push environments. That is historically grown, as the standard was originally designed to standardize communication between business and control systems[4]. All terminology reflects to the PPC domain. For example, the defined object models (capability, schedule, production rules, etc.) are sufficient to implement a scheduling system. But none of the ISA 95 publications contains a link to Lean

[4]Enterprise-control system integration is achieved by using the ISA 95 object models in eXtensible Markup Language (XML) format to exchange information. This practical integration is currently standardized by B2MML.

(control) principles. In addition, the MOM domain is more than only a PPC integration project. It contains all functionality to support production, quality, inventory and maintenance activities. As CI initiatives are highly interconnected with those activities, future ISA 95 publications[5] should pay more attention to them. One of the conclusions of this dissertation is that the modeling of Lean principles and tools is possible with the ISA 95 object models that are currently available. The proposed ISA 95 match with Lean concepts (appendix A) can be used as starting point to generalize the definitions away from the push focus.

3. **MES consultants and integrators:** A lot of MES consultants and integrators use the MOM framework of ISA 95 to set up a URS. This document is used to select (or design) a software system that fits the specific company needs. As CI initiatives are crucial to strive to operational excellence and maintain production visibility, they should be incorporated in the selection (implementation) process for MES. The Lean MES framework serves that purpose. The alignment between CI and MES can be formalized and will be taken into account from the beginning of the project. In addition, featured (Lean) improvements could help to justify the MES investments. It is not trivial to put featured MES benefits against the high installation costs and possible risks. As a whole, the Lean MES framework can be used to expand (or restructure) an existing Lean MES (brownfield) or to configure one from scratch (greenfield). The idea of integrating standard CI tools and techniques can be applied on an existing application. For example, if an ISA 95 structured ODS is available, then the developed aVSM methodology can be applied, regardless of the specific company situation. Or - as will be done for the case studies in section 4.2 - the available historical information can be transformed to ISA 95 models, to enable the standard aVSM analysis.

4. **MES software vendors:** The Lean MES framework defines a standard approach to combine production visibility with process improvements. In theory, the reconfiguration possibilities would be unlimited. MES is already known as a company specific software. The idea of also adding flexibility and CI support to MES makes it even worse. MES software vendors face the challenge of implementing the concept to a practical solution. However - considering that all MES and Lean functionality is structured in the MOM framework - change work flows would automate the (re-)configuration of the software while maintaining the integration between all activities. That would enable the custom design of a standard analytical workbench on top of real-time data collection. In practice, a number of standard configurations - e.g. for the different manufacturing sectors: food, pharma, metal, industrial machinery, etc. - could be set up as typical starting point. From there on, further configuration can be initiated in order to fit the specific requirements of the customer. For example, the requirements for custom reporting can be specified in

[5]Part 4 & 6 are still unpublished. As they will describe the internal MOM content and information flow, a more generalized approach would certainly be worthwhile.

order to collect the right information at the right time at right place in production. Or production control principles can be set up to connect all processes in order to achieve an optimal product flow. Or different optimizing rules can be made available to select from in various situations: e.g. rush order, limit setup time, maximize throughput, etc. Based on the Lean MES framework, the commercially available software packages could be tested on Lean MES conformity. How easily can they be configured at the start and reconfigured during operation? Are the required reconfiguration options available for a specific company case?

5. **MES end users and Lean practitioners:** Eventually, the end users of both strategies will benefit from the research efforts. A Lean MES will fix the shortcomings of both approaches. MES will be more user friendly, up to date, flexible, etc. because of Lean information management. The MES visibility can drive the Lean journey, validate future states, suggest CI initiatives and impose the improved way of working.

## 3.3 Standard integration of Lean

By integrating Lean tools and techniques within MES, they can benefit from its data and analysis support. To achieve this integration, Lean functionality must be matched to ISA 95 terminology. Awaiting the publication of part 4 of ISA 95 (which will describe the information exchange within the MOM layer), the object models of part 1 & 2 will be used to model the integration. VSM - a crucial Lean practice at the start of the Lean journey - will be described as an example. There are two main reasons why the VSM integration is tackled first:

1. **Lack of attention to flow efficiency in MES:** From an operational point of view, CI initiatives in MES mostly focus on resource efficiency. Typically, the goal is optimizing the individual OEE values of the resources. Different CI initiatives are set up to increase availability, performance and quality. In the context of TPM, many MES software systems already incorporate OEE calculation, analysis and reporting. For example, a Pareto analysis of machine breakdown causes can determine the most urgent improvement areas. Or the application of six sigma can bring product quality within acceptable limits. However, there is still room to improve the analysis support to select and follow up the CI initiatives. Efforts rarely exceed the use of spreadsheets or stand-alone software tools that require intensive human interaction.

   Flow is one of the key aspects of Lean manufacturing[6]. Unlike process kaizen, there is currently little to no support for flow kaizen within MES. Process efficiency is the combination of resource efficiency and flow efficiency. In the *Nirvana* state, both efficiencies are 100%. Reaching process Nirvana is very hard, possibly even impossible. But even if it is impossible, striving for it will pay off. If you can have higher flow and resource efficiency than your competitors you can outperform them. You need to choose a strategy to contain your variation, increase your flow efficiency without lowering your resource efficiency. VSM is a typical Lean tool to visualize production flow. A number of typical Lean metrics (e.g. Product Lead Time (PLT), Ratio Value Added (RVA), etc.) can assess the flow efficiency of the value stream. Through CI initiatives, an attempt is made to go from current to future state. As MES support for flow kaizen is currently underdeveloped, a detailed description of the integration of VSM in MES (i.e. aVSM) is tackled first.

2. **VSM coordinates other tools and techniques:** The VSM methodology covers a number of other initiatives. During the Lean implementation phase - to go from the current to the future state - pull control systems (e.g. kanban controlled supermarket) are introduced and CI initiatives are launched (e.g. SMED, 5S, layout changes, etc.). The VSM analysis coordinates the whole and assesses the Lean progress.

[6] By creating flow, less inventory must be maintained and consequently small product lead times can be achieved.

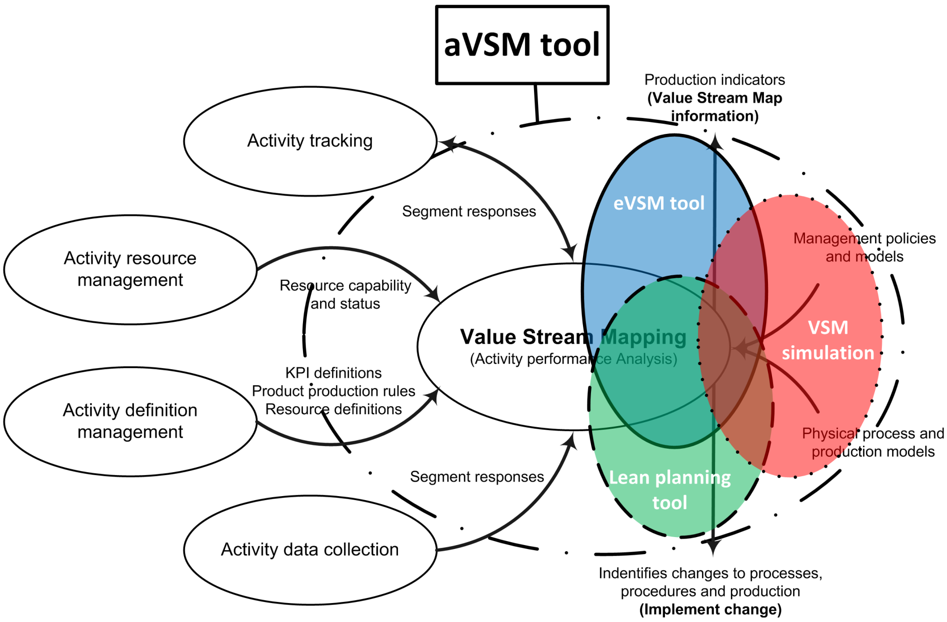



*Figure 3.5: Detail of the MOM framework related to aVSM (Adjusted from ISA 95 (2000))*

In addition, the steps to expand the framework with other Lean tools and techniques are described. A number of examples is listed to illustrate the concept. The framework could also be extended with a certain intelligence to propose appropriate Lean metrics, tools and techniques for a specific production environment and situation.

### 3.3.1 aVSM methodology

VSM is explored as an example. A good alignment with an MES - where a lot of data are already available - can speed up the analysis. A tool that can automatically perform the complete construction and analysis of VSM is not the goal. The human input will always be the driving force of the exercise. But MES can deliver meaningful information to generate an eVSM template to start from or to validate the manual result. When the information from MES does not match the manual result, then something is wrong. As well a wrong manual exercise as information errors in MES are not acceptable and must be corrected somehow. In addition, the VSM methodology can be embedded within MES to help structure the standard work flow of the analysis. MES can guide, assess and support the Lean progress. The functionalities, currently offered by standalone applications; such as Lean planning tools, VSM simulation, eVSM; can be merged together and integrated with MES. Figure 3.5 shows part of the MOM framework that is useful in the case of VSM, which is contained within (or connected to) the activity *performance analysis*. The different VSM phases can be structured as (part of) the content of the activity. The nec-

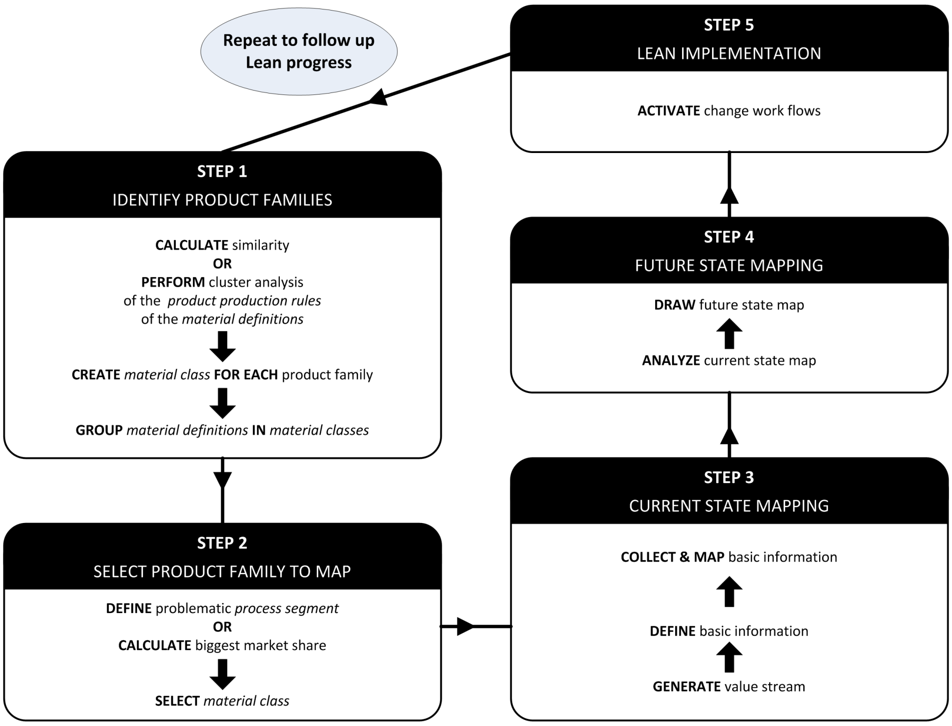



*Figure 3.6: The standard phases of the aVSM analysis*

essary integration is then visualized through the different information flows to and from other MOM activities. The current available VSM tools are mapped on figure 3.5. By integrating these activities within MES, the support can cover the whole area, resulting in an (semi-) automated VSM (aVSM) tool. Based on the standard phases of the VSM analysis, the necessary content and integration of the activity *performance analysis* (or more detailed, the subactivity aVSM) is discussed: identify product families, select initial exercise, map the current state, map the future state, manage the changes and follow up the Lean progress. Figure 3.6 summarizes the different phases applied to aVSM. Appendix A provides a detailed overview of the match between Lean and ISA 95 terminology, with a focus on aVSM. An explanation about the different ISA 95 models, that will be used in the next sections, can be found there.

#### 3.3.1.1 Identify product families

In a first step, the product family that will be mapped must be identified. Similarities between product work flows are searched to define product families. The identification and selection of product families are mostly performed purely manual. By integrating Lean into MES, software support can assist this first step in the analysis. The (*definition* or *tracking*) object models within MES can be used to analyze the commonalities between different product routings to identify product families. Based on this information a simple similarity percentage can be calculated or more complex clustering algorithms can be used to create optimal product family groupings. Each product family must be represented by a separate *material class* and contains the different final products as *material definitions*. After this initial classification, product families can be critically reviewed on a regular basis or after new product introductions.

#### 3.3.1.2 Select initial exercise

The selection of the first product family to map and analyze may be straightforward in most cases. Typically a product family with promising Return On Investment (ROI) opportunities will be tackled first. Product families could be automatically prioritized based on available historical information. For example, problematic processes could require the first focus. Focusing on product families that consist of high quantity or high revenue products is advisable to enable quick wins. MES incorporates the actual produced quantities of final products. Summing these values over a certain period of time gives an idea of the product mix. The product family with the biggest share is an appropriate candidate for the initial exercise.

#### 3.3.1.3 Current state mapping

To map the current state using VSM, you must walk the process. However, as stated in section 2.4, the available historical data in MES can be used to support the manual exercise[7]. A number of configuration steps are necessary to determine what will be mapped and to integrate the generation of the current state map within ISA 95. The VSM tool itself allows for flexibility to work within any setting, but still boundaries exist. The rules that do exist focus on three elements (Nash and Poling, 2008) and will be used to explain the integration requirements:

- *Standardization of icon use, as much as possible*
  The basic icons used in VSM are a combination of flowcharting icons and unique shapes used to visually represent the various tasks and functions within a map. A detailed description of the icon mapping to ISA 95 is listed in appendix A.2.

- *The basic layout of the map*
  All maps are alike. Communication appears on top. Process or product flow appears in the middle and always flows from left to right. Timelines and travel distances are shown on the bottom. Process boxes, push and pull arrows, inventory locations and communication lines are always used in a similar fashion. This standard layout enables the development of a support tool for one or more of the stated compartments

[7] Using the eVSM template as starting document can expose problems or wrong data in MES. Another option is to validate the manual exercise by the generated eVSM template. Contradictions must be investigated to expose and correct manual or MES errors.

of the current state map. The support MES can give, depends on its implementation level and on the information that is available.

- *Creation of a structured method of documentation and presentation to make the results clearer to the audience*
  The drawing steps for the aVSM case must follow the same structured method as the manual exercise. aVSM - as part of MES - imposes the standard analyzing steps, sends requests for (available and/or future) information to other activities and generates a template that can be completed further by walking the process. This work flow for drawing the current state map consists of three steps:

```
procedure GENERATEVALUESTREAM(material class)
    for all material definitions in material class do
        Connect(material definition)
    end for
end procedure

procedure CONNECT(material definition)
    SR ← segment responses where material produced actual = material definition
    for all process segments corresponding to SR do
        Draw process segment information on map according to the segment type
        for all materials consumed actual in corresponding segment response do
            Connect(material consumed actual)
        end for
    end for
end procedure
```

*algorithm 1: Generate the value stream of the current state map for a given product family*

1. **Select the product family and generate the value stream**
   A list of product families was created previously and all material classes (containing final products) are now enlisted as options. After selection, some general information about the selected product family can be drawn on the top of the map (e.g. product family name, final products contained, etc.). Algorithm 1 shows the basic steps in order to generate the value stream of the current state map for a given product family. As in the manual case, the map is drawn in opposite direction of the value stream itself. The last step of the value stream is the process segment of which the corresponding segment responses have a final product(s) (material definition) of the product family (material class) as *Material Produced Actual*. Then, for each *Material Consumed Actual* of the segment responses, the next process segment(s) (with that material type as *Material Produced Actual*) is (are) drawn in front of the previous one. These steps must be repeated until the beginning of the value stream, the receiving of the raw materials. In algorithm 1, the recursive calling of procedure

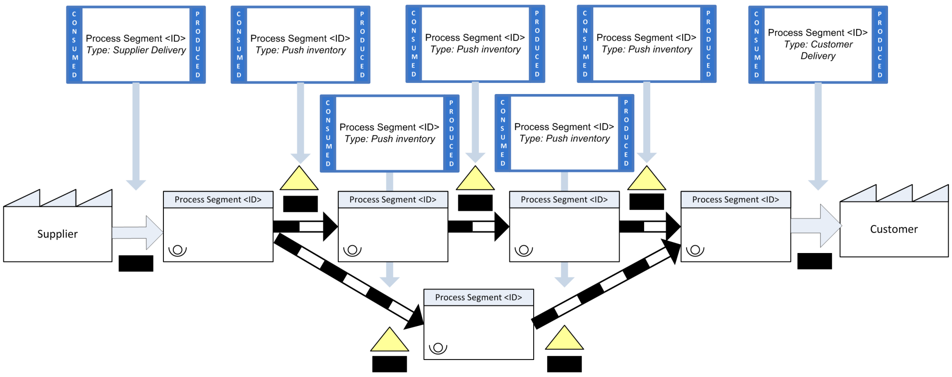



*Figure 3.7: The generation of the value stream based on ISA 95 objects*

*CONNECT* makes sure that all paths within the value stream are drawn. The material definitions are the glue to connect the different process segments of the material flow. The process segments are drawn with the VSM icon *process box*. In a next step, the flow signals between the process segments must be documented. As inventory (and transport) activities also can be considered as operations, each one is represented by an additional process segment. Figure 3.7 shows the value stream configuration based on ISA 95 objects.

2. **Define basic information about the current state**
   Basic information must be added to the map. Below each process box on the map, a *data box* icon is drawn. The provided information is listed and, when extra information is necessary, extra properties (or parameters) can be configured to list additional values for each process segment. Appendix A.3 provides a more detailed description of the ISA 95 translation of a number of standard VSM facts and their calculation method. Figure 3.8 gives a possible result of a data box of one of the processes of the value stream after the definition of the basic process information. The black areas symbolize the required information to fully document the map.

3. **Collect and map the basic information about the current state**
   In an attempt to facilitate Lean information management within MES, a pull-based information flow is initiated. The information requirements for aVSM result in information requests to other MOM activities; such as *resource management*, *definition management* and *tracking*. To be able to generate the necessary information, each activity, for its part, requests data from the activity *data collection* to populate its model structure. For *tracking* purposes, segment responses must be created for each executed task. This information is delivered to data collection by the activity *execution management*. When a time frame of historical data is already available, then the necessary calculations (see algorithm 2) can be performed. Computed values are automatically

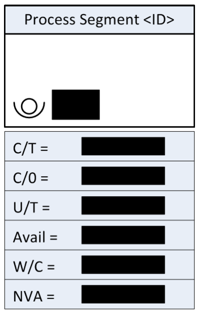



*Figure 3.8: A possible result of a data box after the definition of the basic process information*

updated on the map, missing values leave blanks that can be filled in manually on the map. However, the ISA 95 model structure was modified in such a way that future data collection will enable automated calculations for the next mapping exercise.

```
procedure MAPBASICINFORMATION(umbrella process segment)
    for all process segments connected to umbrella process segment do
        for all parameters in process segment definition do
            if historical data available in segment responses then
                Calculate value with defined formula OR read value if already available
                Add information to the map
            else
                Add empty box to the map (to add value later during manual analysis)
            end if
        end for
    end for
end procedure
```

*algorithm 2: Add the basic information on the value stream map*

The result of these steps is a current state map of the value stream conform the standard mapping rules. The available historical information within MES is structured on the map. Missing values are indicated and can be added later on during the manual efforts. A good integration within MES imposes standard work during the VSM analysis. The model requirements for ISA 95, to structure the data support, were emphasized. A number of situations were already mentioned where ISA 95 object models were modified to collect extra manufacturing information to support future VSM exercises. In section 3.4 the role of these change management efforts will be further described.

#### 3.3.1.4 Future state mapping

Just as the current state map is a visual representation of the process as it actually operates today, the future state map is intended to indicate how the value stream could operate more efficiently. The future state map is a blueprint for change. The human input is the driving force of this exercise, in order to identify and remove the waste on the current state map. Brainstorming sessions must result in a future state map, showing the new situation and the necessary changes to achieve it. The *kaizen burst* icon shows what must be done to make each change a reality. A number of key actions guide the analysis toward the future state (Rother and Shook, 1999): Produce to takt time; develop continuous (one-piece) flow; Use supermarkets where necessary; schedule based on the pacemaker; level the production mix at the pacemaker; level the production volume; EPE 'time period' and process improvements. For each action, the proposed ISA 95 representation is discussed in appendix A.1. The related model state changes to incorporate the modified production control are listed in section 3.4.

#### 3.3.1.5 Lean implementation

A Lean implementation plan is initiated in order to achieve the documented future state. If the new state is introduced on the production floor, then MES must fully incorporate these changes in order to support the new way of working. By performing an appropriate sequence of standard change work flows, MES support for the future state can be achieved. Typical kaizen bursts are added to the map stating important (follow-up) actions. The change management approach to enable these Lean changes is presented in section 3.4. The migration of the ODS to the future state will provide all MOM activities with the necessary information for the newly introduced production control. When the downstream inventory control of a production process is of the type *Push inventory*, then the communication flow for a typical push environment will define the actions for the MOM activities. In case of pull production control, activity tasks will be adjusted. Appendix A.4 provides a detailed description of some pull configurations in ISA 95 terminology.

#### 3.3.1.6 Follow up Lean progress

The change management of MES does not only support the new way of working. It also enables MES to redraw the current state when (part of) the Lean changes are implemented. The given VSM representations of the typical current state (Push) and future state (Pull) value stream by ISA 95, make it possible to support the construction of VSM at all times, also for hybrid situations (to assess intermediate results). After a certain period of time, the current state map can be redrawn. That enables an evaluation of the new way of working and - where necessary - further changes can be introduced. The Lean planning system and the performance evaluation are closely integrated to achieve an efficient Lean transformation.

### 3.3.2 Future expansion of the framework

The architecture of the Lean MES framework (as previously shown in figure 3.4) is built around a common ODS. The ODS contains all master and operations data in ISA 95 format. All activities share that information. A new functionality can be plugged in on the MSB to expand the framework. In order to achieve an instant integration within the whole, the ODS integrity must be maintained. Therefore, two requirements must fulfilled:

1. The Lean tool or technique must use standard ISA 95 terminology to perform its task.
2. Standard change work flows must be defined to make the ODS follow the implemented Lean changes. That way, the ODS integrity is maintained at all times.

#### 3.3.2.1 Other Lean tools and techniques

Total Productive Maintenance (TPM) is an improvement strategy that creates the awareness that everyone is responsible for improving resource efficiency. It is a goal that only can be achieved if all personnel works together on small incremental improvements. Just like VSM, TPM incorporates a number of standard tools and techniques that can be used to reach the goal. Lean progress is typically assessed by OEE scores. A Pareto analysis can indicate the next problem to tackle. Multidisciplinary improvement groups determine causes and effects of the problem by Ishikawa diagrams. The PDCA cycle is used to guide the improvement, e.g. execute SMED. At the end, the effect on OEE is checked. To maximize the operator involvement, visual management tools (e.g. TPM boards) are installed to visualize the TPM teams, actions and progress. Two actions are required to add TPM support to the Lean MES framework:

1. **Data and functionality mapping to ISA 95 terminology:** A detailed description of the ISA 95 mapping of the different tools and techniques is set as future research, but an idea of the approach is given.

   - OEE: To enable the construction of this KPI, operations data are required. The different components where discussed in section 2.3. The OEE score is assigned on an *equipment* or *process segment* level. There are a number of calculation variants. Based on the selected formula, information requirements are set within the *data collection* activity.
   - Pareto analysis: Support for this technique requires operations data about the occurrence of the different problems. The various events (e.g. machine setup, breakdown, operational stop, etc.) must be logged as *Segment response* objects of each *process segment* by the *tracking* activity. Standard attributes - such as start time, end time, description - can be accompanied with more specific event data (extra properties).
   - Ishikawa diagrams: In a manufacturing context, 6 M's are associated with a specific problem to determine the problem causes: Machine (*equipment*),

Method (*process segment*), *Material*, Man power or Mind power (*personnel*), Measurement (*KPI definition*) and Mother nature. Four of the six M's coincide with the basic ISA 95 resource models.

- PDCA: The progress of the different improvement initiatives can be monitored. Which *process segment* is under improvement? What is the status of the improvement? Who is in charge of the next step (*Person*)? Who will check the actual improvement (*Person*)? What are the associated measurement values (*KPI definition*)?
- SMED: There is a high similarity with the aVSM methodology. But now, the value stream consists of a sequence of tasks (*process segment*) that need to be executed to achieve a product changeover.
- Visual management: Performance information that is available in MES can be visualized in real-time for all operators.

2. **Definition of standard change work flows:**

   - Configure OEE scores with custom reporting: This change work flow is identical to the one discussed for the construction of the current state map from VSM. The standard OEE formula is listed in appendix A as VSM fact.
   - Set information requirements for the various machine events in support of the Pareto analysis.
   - Implement a work flow management system that imposes the task sequence for product changeovers.
   - Configure visual management screens with the custom reporting work flow.

#### 3.3.2.2 CI intelligence

Currently, only support for the execution of Lean tools and techniques is discussed. The literature review about Lean (section 2.2) mentioned research initiatives that try to model the interrelationships between manufacturing problems, Lean metrics and Lean tools and techniques. Based on the available operations data, MES could suggest future CI initiatives to boost performance. This selection algorithm will depend on different parameters such as manufacturing sector, business strategy, company specific KPI's, etc.

## 3.4 MES/MOM change management

During the Lean journey, a structured change management approach is necessary to be successful. People, organizational structure, technology and processes are important pillars of change and need to interact appropriately to handle its complex nature (Bell, 2005; Wigand, 2007). Let us assume that an appropriate Lean analysis was performed with support of the aVSM tool. Management fully supports the Lean journey. Operators have sufficient knowledge and understanding of Lean. Process flow and layout were successfully modified to suit the future state. Then the only question that remains, is: How can production control of MES; as Lean IT system; be implemented (greenfield) or adjusted (brownfield) to follow these typical Lean changes on the production floor?

An ISA 95 based change management process supports the development of change work flows for ongoing operational change and provides a basis for developing a full-scale change management process to facilitate implementing major system and process changes (Gifford, 2007). However, not only can ISA 95 guide the change work flow, it can already perform a great deal of the work of standard Lean (operational) changes by incorporating the change work flow structure. Historical data and other model definitions can support standard changes. This support can reduce the change-over time and possible errors within MES, having a positive influence on the TCO. The support for a number of operational changes, that relate to aVSM, are discussed.

### 3.4.1 Influence on Total Cost of Ownership (TCO)

Goodness of fit and flexibility of software are often conflicting goals. Custom coding can deliver an ideal system at the time but generate excessive costs to maintain, reconfigure or adapt the system in the future. At the other hand, a standard system may require to alter the normal way of working of the company and result in an efficiency decrease or perhaps a loss of competitive advantage. An off-the-shelf solution represents an approach that requires a company to adopt best practices, but not necessarily those best suited to the company, possibly resulting in failure. A good balance must be strived for to minimize the TCO. Figure 3.9 (a) gives a simplified graphical representation of this optimal fit. The different cost parameters are described in Table 3.1. The actual cost values (and their ratio) can strongly vary from case to case, but an idea is given of the typical trending. Focusing on this optimal point must compensate for the natural tendencies toward over-complication, over-automation and rigidity, in order to realize the benefits of Lean IT (Bell, 2005). The possible effect of an efficient MES/MOM change management approach is drawn in figure 3.9 (a). The coding and maintenance cost can be reduced, resulting in a lower overall cost for a better fit to requirements at the new optimal fit. After the initial MES adoption, Lean IT must manage change incrementally and continuously to be able to achieve full system potential (Bell, 2005). That phased implementation plan of the MES adoption is shown in Figure 3.9 (b).

Three types of MES changes are identified: updates, operational changes and model changes. Updates are small incremental (automated) software improvements to fix errors

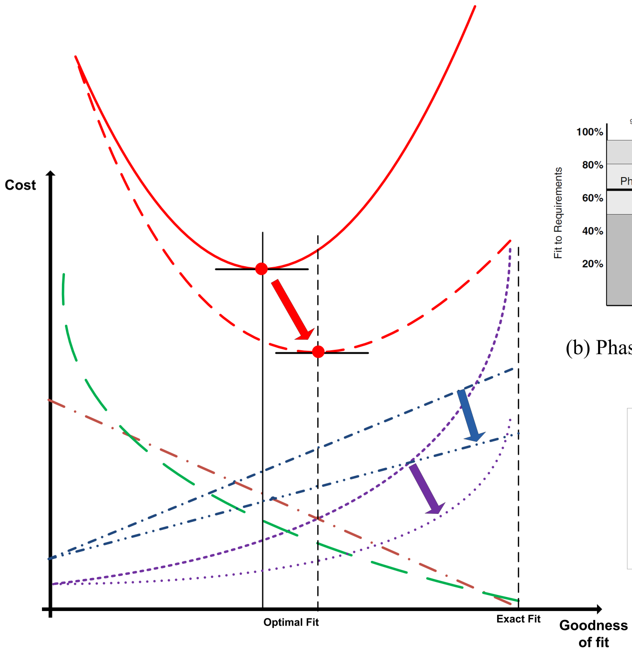
| Cost parameter | Description |
|---|---|
| **Coding cost** | The cost for custom coding activities to make the solution fit the requirements. This cost increases linearly with increasing goodness of fit. Configuring a standard solution normally requires less effort than creating an application from scratch, resulting in a smaller slope of the curve. But license costs cause a higher starting point on the Y-axis. |
| **Efficiency cost** | By automating information flows, efficiency is increased in normal operation. Working without MES results in a penalty cost, that decreases gradually by increasing goodness of fit. This penalty reaches zero when MES exactly fits the requirements. |
| **Usability cost** | MES needs to be user friendly in its interactions with operators, managers, etc. and needs to be adjusted to the company's way of working (and not the other way around). Operational changes (new product definitions, new equipment, new reports, etc.) must be supported. A penalty cost is associated with this usability and increases with decreasing goodness of fit. The exponential curve denotes the importance of the social acceptance of the system. The value of a software system highly depends on the way it is used. |
| **Maintenance cost** | Creating an application that perfectly matches the current situation, greatly increases the possibility of change and the associated costs to maintain, reconfigure or adapt the system in the future. The exponential curve illustrates the increasing effect when approaching exact fit. |
| **Total cost** | Adding all costs creates an overview of the TCO of MES accounting direct (coding) costs, indirect (maintenance) costs and benefits (efficiency and usability). The presented elements are not very detailed but serve the purpose to explain the change management balance. |

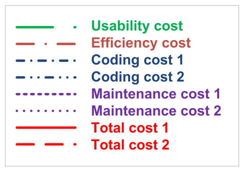
*Table 3.1: The meaning of the different cost parameters considering MES change management*

and bugs or to boost performance. These deviations to the requirements usually come to surface from the moment the system is actually being used. Operational changes are changes introduced within the boundaries of a company's existing MOM model (e.g. a new product introduction, installation of a new equipment, a revised product flow, etc.). MES supports these changes by offering the ability to modify its internal structure and information through a predefined change workflow. An efficient and user-friendly human machine interface must enable these changes and guard the integrity of the MES data models and information flows at all time. The support for operational changes is part of the system requirements. The (balance of) costs associated with these changes are incorporated in the coding and usability cost. Changes that alter the company's MOM model (or the current structure of MES), are referred to as model changes. These changes are more radical (and as a consequence more expensive) because they require a change of the system itself. By using ISA 95 based change management the coding and maintenance costs - associated with operational and model changes - can be drastically lowered. In addition, standard ISA 95 change work flows can be constructed to transform the costly model changes to operational changes. What results in the effect previously shown in figure 3.9 (a).

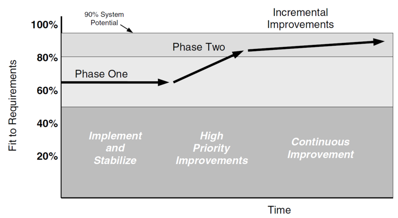
### 3.4.2 Support for Lean operational changes

Within the MOM framework of ISA 95, standard model changes can be incorporated. The ISA 95 object models can be used as a uniform manufacturing structure and terminology. Operational changes, based on ISA 95 model transitions, can be configured quickly while the costs are restricted to a minimum. Adding new equipment is a relatively small change




(a) Influence of an efficient change management approach on the TCO of MES




(b) Phased implementation plan for Lean IT (Source: Bell (2005))

*Figure 3.9: Change management aspects for MES*

in MES, because it only affects one resource model, equipment, within the activity *resource management*. However, complexity may increase when a change affects multiple object models within multiple activities. And even more, when the change spans over multiple subsystems.

The support for a number of Lean operational changes, that were encountered in section 3.3, will be discussed. There is a basic difference between sections 3.3 and 3.4. aVSM (section 3.3) focuses on the structuring and the mapping of the available MES (and manual) information to a current state map. An eVSM template is used to support or validate the manual VSM analysis. As result of that analysis, the eventual future state map is configured in aVSM. MES/MOM change management (section 3.4) is now responsible for translating that future state map to a modified MES model structure. MES must incorporate the new way of working (in combination with future data analysis support) based on the future state map. The different MOM activities base their operation on the ODS content. Changes in the ODS can impact multiple activities. Figure 3.10 gives an example of a migration path of ODS (as model structure of MES) through typical operational changes. The CI solution space for MOM is multidimensional, but standard model changes structure and limit the complexity. The change work flow for a number of operational changes will be presented. The potential impact of a new product introduction on

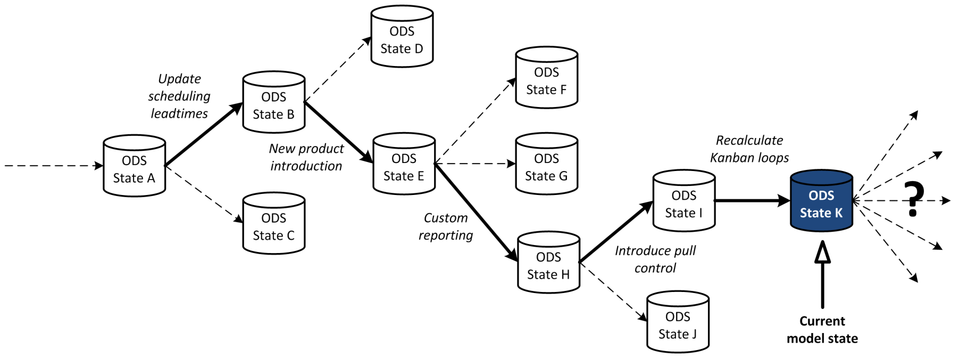



*Figure 3.10: An example of a migration path for ODS through standard model state changes within the CI solution space of MOM*

the different MOM activities is tackled first. Secondly, custom reporting is discussed to serve the changing information needs to support continuous improvement in a production environment. Finally, the change work flow for the introduction of pull production control - as typical Lean transformation - is listed.

The database is constructed based on the ISA 95 object definitions and always stays fixed. Figure 3.11 shows the Entity Relationship (ER) diagram of the MSSQL Server$^{TM}$ database that will be used to illustrate the model state changes of the ODS. To reduce the complexity, only part of the ISA 95 models were considered. The standard model changes affect (modify, add and delete) records in the different tables to impose the new situation.

#### 3.4.2.1 New product introduction

The change work flow is pulled by customer demand. The production manager - as customer at the end of the change value stream - demands a modified MES system that fully supports the production of the new product. That is the value, requested at the end of the work flow. A new product introduction affects object models within the activities *definition management* and *resource management*. The ER diagram of the ODS (Figure 3.11) indicate the steps of the change work flow. In essence, adding a new product, requires an additional record in the table *material definition*. However, the ODS table interrelationships demand extra information about product characteristics (*material definition property*), product family (*material class*), manufacturing steps (*product production rule*, *product segments*) and (possibly) resources (*personnel*, *equipment*, *material*, *process segment*). The change work flow must guide the MES change agent (e.g. production manager) through the required structural extension of the ISA 95 data model. Available historical information or other model definitions can support the process by reducing the required manual input, just asking the user to fill in the blanks. The change work flow is orchestrated within the activity *definition management* and requests information or action from other activities through the MSB. Based on the ISA 95 activity models (MESA

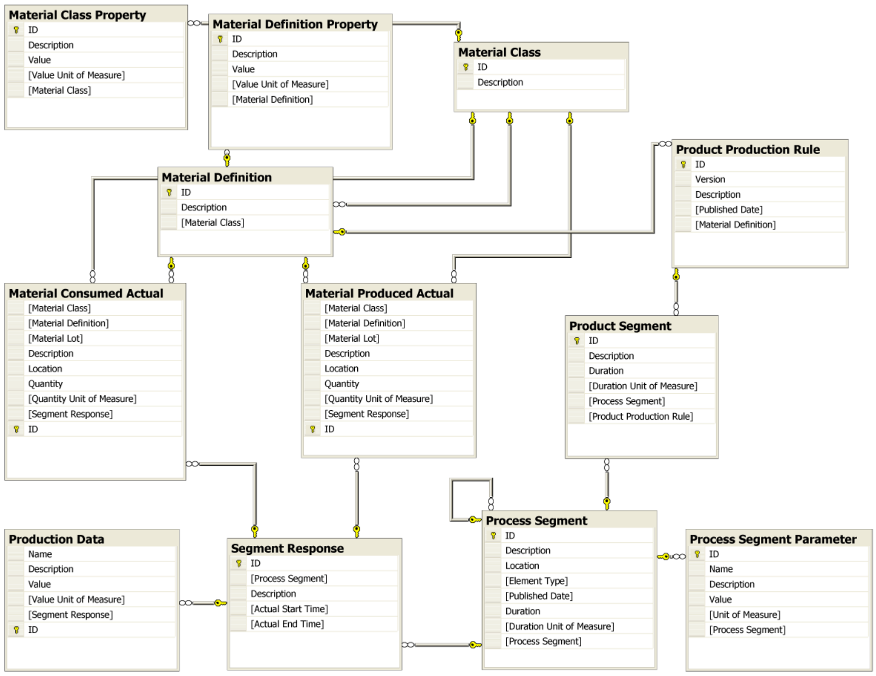



*Figure 3.11: The Entity Relationship (ER) diagram of (part of) the ODS structured by ISA 95 terminology in MSSQL Server™*

International, 2007), the following actions must be part of the work flow:

1. *Information flow to resource management:* Define the new product
   (a) *Task:* Create a new *material definition*
   (b) *Task:* Add the new material definition to a *material class*
      - *Option:* Add to an existing material class, if the product family is known and already exists
      - *Option:* Create a new material class, in case of a new product family
      - *Option:* Classify later on based on the *product production rule* similarity or cluster analysis
   (c) *Task:* Add Quality test definitions
   (d) *Task:* Ensure that all storage and transfer rules and definitions - associated with the new product - are set up
2. *Task:* Configure the new *product definition* information (Product Production Rule, Product Segments & Manufacturing Bill)

(a) *Task:* Load a product definition template ...
   - ... with structure and information of an existing material definition (the new product is a variant)
   - ... with structure based on the existing product family
   - ... that is empty

(b) *Information request from business level:* Request the product definitions from the business level. If available, merge the information into the template

(c) *Task:* Fill the blanks in the product definition model

(d) *Information flow to resource management:* Ensure that all resource (material, personnel, equipment & process segment) information - that is required to make the product - has a resource definition → Start an appropriate change work flow for each added resource

(e) *Check:* Calculate the commonality of the new product with other final products in the product family to make sure the new product is properly classified

3. *Information flow to execution management:* Ensure that the current SOPs for startup and shutdown are adequate for the new product

4. *Information flow to detailed scheduling/dispatching:* Ensure production control
   - *Push control:* Ensure that the plant's production control is updated with the detailed production routing for the new product
   - *Pull control:* Add local production control support for the material flow of the new product (e.g. add new kanban cards)

5. *Information flow to performance analysis:* Ensure that the plant's performance analysis is updated with targets for the new product

When all necessary information is created to support the production of the new product, then the Lean MES functionality is maintained. Figure 3.12 gives a graphical representation of the framework interactions to support the change work flow for a new product introduction. As an example, the change work flow will be applied to the verification case in section 4.1.

#### 3.4.2.2 Custom reporting

In order to continuously improve within a production environment, information is required to support the analysis. The Manufacturing Intelligence (MI) of MES must convert raw data into meaningful information. During the continuous search for improvement opportunities, information requirements will evolve. Keeping Lean information management in mind, MES must be restructured to fit the customer requirements at all time. To do so, data collection to support new information requirements must be configured. But also, collecting data for old information requirements must be abandoned to eliminate the

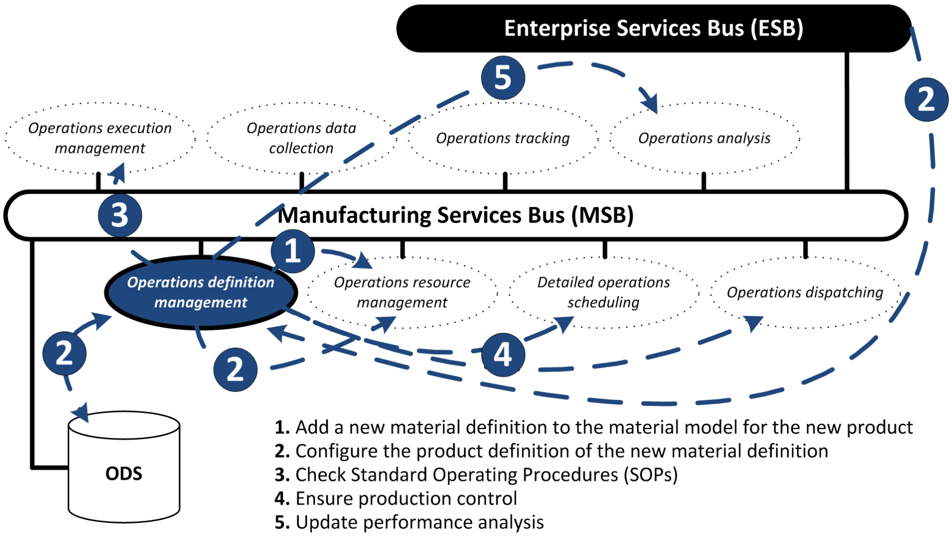



*Figure 3.12: Graphical representation of the change work flow for a new product introduction*

wasteful activities. Custom reporting serves the constantly changing information needs to support CI in a production environment. The activity *performance analysis* locates all functionality to analyze and report performance information. A change work flow must guide the MES change agent (e.g. production manager) through the required structural extension (and reduction) of the ISA 95 data model to follow the changing information requirements. Starting from customer demand (i.e. custom report), a stepwise refinement process configures the information flow. Based on the structure of the ISA 95 activity models, the following actions must be part of the work flow:

1. *Task:* Define information requirements

   (a) *Task:* Define the information requirements for each level in the equipment hierarchy (e.g. site, area, work cell, unit, etc.)

   (b) *Information flow to resource management:* Add properties to the different resources conform the defined information requirements. Each property specifies the information (property name) and will contain the value (properties value & unit of measure).

2. *Task:* Configure data/information collection requirements

   (a) *Information flow to data collection:* Define the data collection requirements based on the empty property values in the resource definitions. The value can be ...

      i. ... a formula (e.g. KPI definition) to calculate the value

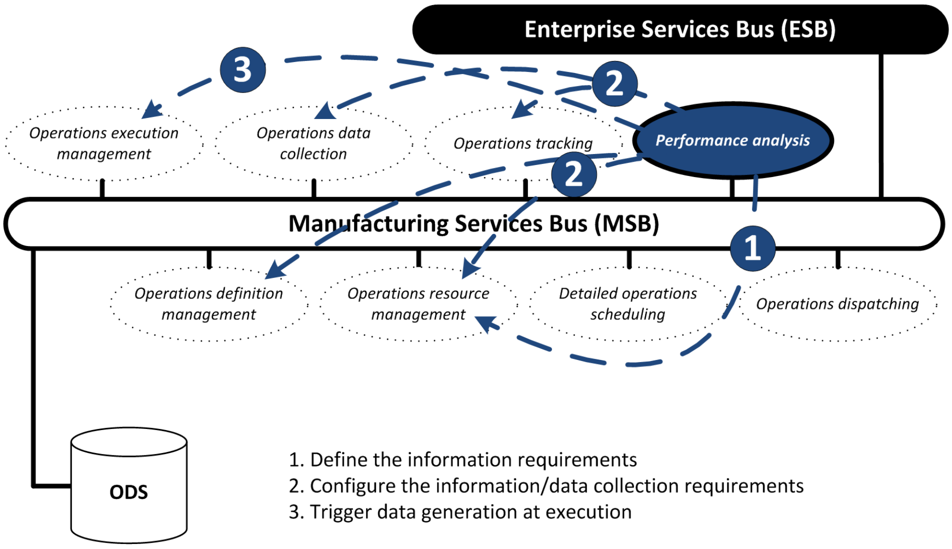



*Figure 3.13: Graphical representation of the change work flow for custom reporting*

ii. ... a data collection tag (e.g. OPC tag)

iii. ... left empty, requiring manual input during analysis

(b) *Information flow to definition management:* Define newly introduced formulas.

(c) *Information flow to resource management:* Define the resource information requirements based on the specified formulas.

(d) *Information flow to tracking:* Operations activity data are recorded by segment response objects. A *requested segment response* object defines the structure of the required information for each process segment. All required information (in addition to the standard attributes) is added as extra *production data* parameters.

(e) *Task:* Iterate steps 2a, 2b, 2c and 2d until all information definitions and data sources are configured.

3. *Information flow to execution management:* Trigger the generation of segment responses during operations execution. Match the defined data sources to control system variables and input. Alter work flow management to provide all data.

Figure 3.13 gives a graphical representation of the framework interactions to support the change work flow for custom reporting. The construction of the eVSM template by aVSM is an example of custom reporting. Typical facts for the process segments on the current state map must be defined within *resource management*. Standard calculations are configured in *definition management*. The segment responses are structured by *tracking* to reflect the additional manufacturing information. *Data collection* connects the data sources and *execution management* triggers data collection. As an example, the change work flow will be applied to the verification case in section 4.1.

#### 3.4.2.3 Transition to pull flow

A typical aspect of a Lean transformation is the introduction of pull flow. aVSM - as part of the activity *performance analysis* - supports the transition of MES, in order to match the future state introduced on the production floor. A change work flow must guide the MES change agent (e.g. production manager) through the required structural extension (and reduction) of the ISA 95 data model to follow the changes. The result is a modified production control system within MES. Based on the structure of the ISA 95 activity models and the standard VSM steps, the following actions must be part of the work flow:

1. *Task:* The current state map of aVSM is completed by the manual analysis. Step by step, the future state map can now be configured within aVSM. Line balancing introduces possible changes to layout, task sequence, operator allocations or other kaizen bursts, e.g. reduce Cycle Time (C/T) or Change-over Time (C/O).

2. *Information flow to resource management:* Modify the content and the structure of process segments (and possibly other resources) in order to follow the changes introduced by the future state map, e.g. merge tasks, eliminate task, kaizen burst to reduce C/T, etc.

   (a) *Information flow to definition management:* Modify product definitions as result of the modified resource definitions

   (b) *Information flow to data collection*: Modify information/data requirements as result of the modified resource definitions

   (c) *Information flow to tracking*: Modify segment responses as result of the modified resource definitions

   (d) *Information flow to execution management*: Modify the work flow and data triggers as result of the modified resource definitions

3. *Information flow to scheduling:* Configure the modified production control. Only the pacemaker process is scheduled or controlled through load leveling.

4. *Information flow to dispatching:* Configure the new dispatching rules for all other processes. At the pacemaker process, products are pulled from upstream processes and flow through downstream processes. The ISA 95 model representations of typical pull systems were discussed in section 3.3. A general overview is given in appendix A. Downstream of the pacemaker (and upstream where possible) one-piece (or $n$-piece, controlled by a FIFO lane) flow is introduced. Where necessary, a kanban controlled supermarket is installed. Based on the available product definition data, the required kanban loops can be initiated.

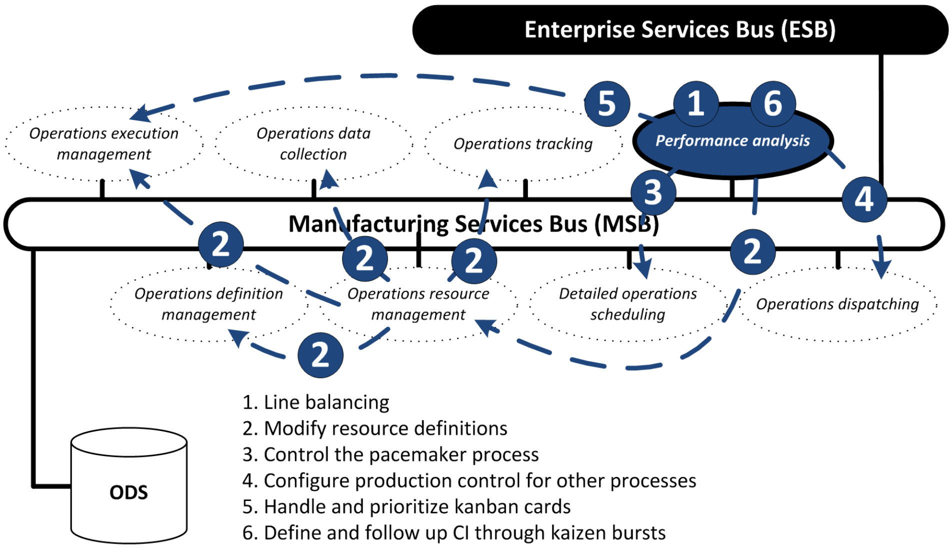



*Figure 3.14: Graphical representation of the change work flow of the transition to pull flow*

5. *Information flow to execution management:* The work flow for the new production control is initiated, such as the handling and the prioritizing of kanban cards, e.g. by kanban wall.

6. *Task:* Define and follow up CI initiatives through kaizen bursts, e.g. fine-tune kanban cards, reduce C/O by SMED, etc.

Figure 3.14 gives a graphical representation of the framework interactions to support the change work flow for the transition to pull flow. All ISA 95 models must be modified in order to support the new production control. As an example, the change work flow will be applied to the verification case in section 4.1.

### 3.4.3 Change management in function of time

Integrating MES and Lean in practice results in an additional difficulty. MES has a dynamic nature. The ODS structure and content changes in real-time. Lean initiatives are static, as they require an offline analysis. A specific approach is necessary to achieve the Lean MES integration. Figure 3.15 illustrates the integration method in case of aVSM. At the start of the analysis, a snapshot is taken from the ODS. An offline analysis is conducted. The future state is configured in the offline ODS in order to run the PDCA cycles. Each improvement activity of the Lean implementation plan is first implemented on the shop floor (change management of people, processes and technology). The last step in the implementation is a synchronization of MES with the offline future state ODS. A change work flow automatically updates the online ODS to impose the new situation. For ex-

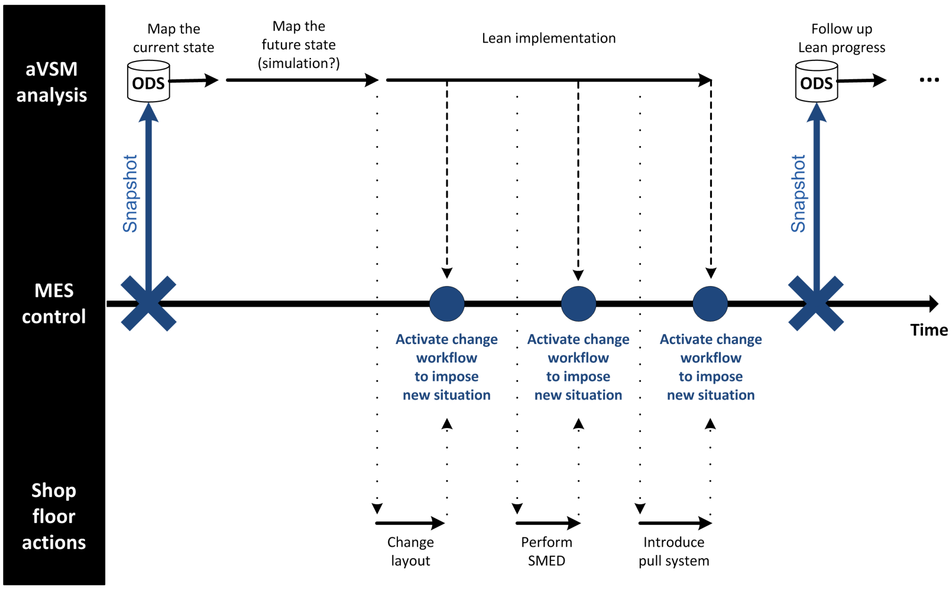



*Figure 3.15: Change management approach for MES in function of time*

ample, when an eKanban supermarket is installed and all operators are aware of the new production control principles, then MES can apply the new way of working. As information requirements are modified during the Lean implementation steps, a new snapshot must be taken to follow up the Lean progress.

Supporting the VSM methodology by MES decreases the lead time of the offline analysis. That means that the improvement can be applied to the shop floor much sooner. The change management of the ODS is performed during the offline analysis. The recorded change work flows can be immediately applied to MES after the shop floor implementations are finished. Both aspects can significantly speed up the improvement cycle.

Version control of the ISA 95 object models is an important topic. Production must always be controlled by the latest version of the models. However, old versions must be maintained to allow redrawing historical value streams, or even restoring the old production control. The *Published Date* attribute of each ISA 95 model determines the date and time on which the model was published or generated.

## 3.5 Conclusion

The MOM definition is part of ISA 95 and was mainly introduced to create a common ground to classify and compare existing MES software systems or integrate different components to seamlessly one solution. However, MOM provides a framework to classify all manufacturing operations, disregarding the fact whether they are performed manually or automated. Therefore, the framework is also introduced to classify the support for Lean practices and as a consequence check the possible alignment between MES components and Lean practices. ISA 95 is presented as a basis for the Lean MES framework that must enable data and analysis support for CI and guide change management to control the achieved improvements. Initial considerations on the Lean MES analysis have been published in (Cottyn et al., 2009a).

The Lean MES framework is structured following the manufacturing 2.0 architecture approach. The MSB of the SOA architecture enables all MOM activities to exchange information. ISA 95 based services enable the communication on the MSB. Each MOM activity comprises functions and tasks, each of which consumes manufacturing master data to execute real-time production and support operations work flows. The extra information about the Lean data and functionality mapping and standard Lean model transitions are added to mMDM, enabling the different activity models (containing Lean software support) to cooperate as a Lean MES.

By integrating Lean tools and techniques within MES, they can benefit from its data and analysis support. MES contains a treasure of historical data that can help the process of waste identification. As IT enabled Lean practices gain popularity, MES is believed to be well-placed to incorporate that support. The integration of VSM is explored as an example. The main reason for the detailed description of aVSM is the lack of attention to flow efficiency in MES. For the data requirements and standard functionality of VSM, a match is made with ISA 95 activity and resource models. Awaiting the publication of part 4 of ISA 95, the object models of part 1 & 2 are used. Product families are identified by product definition information. The standard structure and components of the current state map, are extracted out of ISA 95 based information, and automatically documented on an eVSM template. The eVSM template is used as starting document (or as validation) for the manual analysis. Appendix A provides a general overview of the match between Lean and ISA 95 terminology. This method to align MES with Lean objectives, with a focus on aVSM, has been published in (Cottyn et al., 2009b) and (Cottyn et al., 2011b). A tool that can automatically perform the complete construction and analysis of VSM is not the goal. The human input is still the driving force of the exercise. However, the eVSM template can facilitate the process, reveal corrupted information in MES or expose a wrong manual exercise. The eventual future state map can be configured in MES. The requirements to expand the framework with other Lean tools and techniques are listed for future research.

An effective change management approach of MES itself is proposed to follow typical Lean operational changes. By standard ISA 95 model changes, the new way of working is imposed on the production floor (by redefining the activity tasks) and future data collection requirements are set. That makes it possible to redraw the current state map after a certain period of time. Repeating the aVSM steps, enables an evaluation of the new way of working and - where necessary - further changes can be introduced. A change management approach in function of time is proposed to match the dynamic character of MES to the static nature of Lean. A discussion concerning the role of change management in an MES has been published in (Cottyn et al., 2011a) and (Cottyn et al., 2012).

# 4 Framework Verification & Validation

*The Lean MES framework structures the combination of MOM digitization and MOM optimization. To illustrate the concept, section 3.3 discussed aVSM as the combination of MES functionality (digitization) and VSM methodology (optimization). Table 4.1 summarizes the different phases of the approach. For each phase, the necessary Lean MES support is documented by a number of activities. It is not an exhaustive list, but it is considered to be sufficient to serve the purpose of this research. The Lean MES activities make use of the ISA 95 models to perform their tasks. To be able to represent and implement the Lean principles, a different application of the (original) ISA 95 models is proposed. The affected models for each step are documented. Through a number of cases, the different steps are verified. The mapping of the cases to the featured activities is shown in table 4.1.*

*A lack of real test environments for MES concepts makes it very difficult to validate them. As a first step, the feasibility of the Lean MES framework will be checked. Is it able to do what it was designed for? Does the described input (= match Lean with ISA 95 terminology), result in the promised output (= standard Lean support)? Section 4.1 explores a simulation example in order to verify the feasibility of the proposed aVSM methodology. However, how accurate the simulation model may be, it is always an abstraction of the reality and can not fully represent the complex dynamics of a production environment. In order to fully validate the Lean MES framework, its ability to support a company to discover opportunities, guide the process, achieve the goals and maintain improvements of CI initiatives must be checked. This validation of the Lean MES framework is described in section 4.2. Two companies were selected for an offline analysis. The selected cases each illustrate a different setting for the application of the framework. Case A features a big beverage manufacturing company. The batch processes are highly automated and*

| Nb | Phase | Lean MES activities | ISA 95 application | Sim. Case | Case A | Case B |
|---|---|---|---|---|---|---|
| ● | **Populate ODS with historical data** | New product introduction<br>➠ Add final products<br>➠ Add processes<br>➠ Add production definition | Resource & definition management<br>➠ Material definition<br>➠ Process segment<br>➠ Product production rule | ✔ | ✔ | ✔ |
| | | Custom reporting<br>➠ Add information requirements<br>➠ Add information definitions<br>➠ Add tracking information format | Resource, & definition and tracking management<br>➠ Process segment parameters<br>➠ KPI definition<br>➠ Requested segment response | ✔ | ✔ | ✔ |
| | | Add operations data | Segment responses & production data | ✔ | ✔ | ✔ |
| ❶ | **Identify product families** | Construct product matrix | Create a material class for each product family | | ✔ | |
| | | Perform cluster analysis | Group the material definitions in the material classes | | ✔ | |
| ❷ | **Select product family to map** | Determine highest share of produced quantities | Link quantities of material produced actual of segment responses to product families | | ✔ | |
| | | Use problematic process | Link process segment to product family | | ✔ | |
| ❸ | **Current state mapping** | Generate the value stream | Segment responses, material produced actual & material consumed actual (algorithm 1) | ✔ | ✔ | ✔ |
| | | Collect, calculate and map information | Segment responses & production data (algorithm 2) | ✔ | ✔ | ✔ |
| ❹ | **Future state mapping** | Expose wrong or missing MES values | Process segments, segment responses & production data | | ✔ | ✔ |
| | | Identify waste<br>➠ Takt time calculation & line balancing<br>➠ IN/OUT diagram | ➠ Segment response, material produced actual & process segments (equation 4.1)<br>➠ Segment response, material produced actual, material consumed actual & process segments (algorithm 4) | ✔ | | ✔ |
| | | Eliminate waste<br>➠ Layout reconfiguration<br>➠ Introduce pull supermarket (kanban loops)<br>➠ Kaizen bursts | All activities<br>➠ Process segment<br>➠ Process segment & segment requirements (algorithm 3)<br>➠ Process segment parameter | ✔ | | ✔ |
| | | Check future state (VSM simulation) | Process segments | ✔ | | ✔ |
| ❺ | **Lean (MES) implementation** | MOM change management | standard change workflows | ✔ | | ✔ |
| ❻ | **Follow up Lean progress** | PDCA, Lean planning, evaluate kaizen bursts | Process segments | ✔ | | |

*Table 4.1: Overview of the different phases of the aVSM methodology, the corresponding Lean MES activities, their ISA 95 representations and the mapping to the case studies*

*production control has already some software support. Case B analyses the situation of a small furniture manufacturing company. The production processes have a highly manual character and the discrete process has currently limited software support. In both cases, the usability of the framework to integrate standard Lean functionality on top of historical data is shown. However, the two cases are insufficient to really validate the approach. From the experience of both cases, the future validation requirements are set.*

## 4.1 Framework verification

A simulation example is constructed to verify the concept of the Lean MES framework. The purpose is not to test architectural and technical issues, but to check the feasibility of the proposed Lean MES integration using ISA 95. At one hand, ISA 95 serves as a common data model for operations data (i.e. ODS), on the other hand ISA 95 structures the change work flows in support of operational changes (i.e. mMDM). A pilot implementation example must verify if the presented framework is able to do what it is designed for. Does the presented match between Lean and ISA 95 terminology result in standard Lean support? A fictitious manufacturing example is constructed to explore the feasibility of the proposed aVSM methodology. Simulation software (i.e. Flexsim™) models the manufacturing process and part of the MOM support.

### 4.1.1 Simulation case description

The fictitious manufacturing company *CharBox Corporation* makes aluminum characters contained in a box that comes in two different formats, type A and type B. There are 40 different characters: 'A-Z', '0-9', '/', '+', '-' and '='. So, in theory there are two final products, *final box A* and *final box B*, but in practice, there exist a lot of variants due to the possible character combinations present in the box. Box type A is used when there are 30 or less characters, otherwise box type B is required. A possible order is: 'ARC6HO9LHR=EZ+S-XAPM'. Box A would be used because there are only 20 characters. The average daily demand is 117 final boxes. On average, an order contains 35 characters. The character mix is considered to be random, resulting in similar demand rates for all characters on the long term. Figure 4.1 represents the process flow in order to manufacture the CharBoxes. Standard aluminum sheets are the only raw materials of the production process. They are delivered by the supplier at the start of each week. At arrival, standard sheets are packaged by ten on a pallet. Operators at *receiving* handle the pallets and store the standard sheets in the *standard sheet warehouse*. The *aluminum cutting* equipment can convert one standard sheet into two sheets format A, one sheet format B or ten sheets format Char. Shifting between those three types requires a fairly large changeover time. Sheets of format A and B can be folded (*box folding*) and welded (*box welding*) to boxes A and B. In between folding and welding, boxes are stored in the *folded box warehouse*. Each sheet format Char is converted to ten characters (of the same type) by *character punching*. Again, a changeover is necessary to switch between character types. Boxes and characters are stored in the *preassembly warehouse*. At the *assembly* operation, customer orders determine the content of each final box. These final boxes are packaged (*packaging*) and prepared for *shipping*. Two times a day, a distribution of final boxes to customers takes place.

The CharBox production process is modeled in Flexsim™. Production control is currently a typical case of push flow. A high safety stock level is maintained, to anticipate customer demand variation and unforeseen circumstances[1]. All processes are centrally

[1]However - as the simulation is not a goal on itself - the model will be kept simple. There is little demand

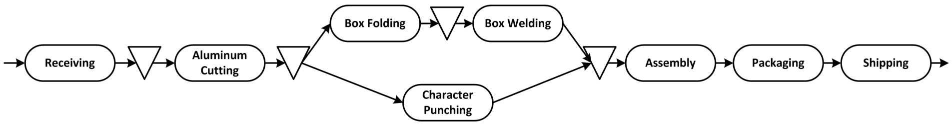



*Figure 4.1: The process flow of the fictitious CharBox company*

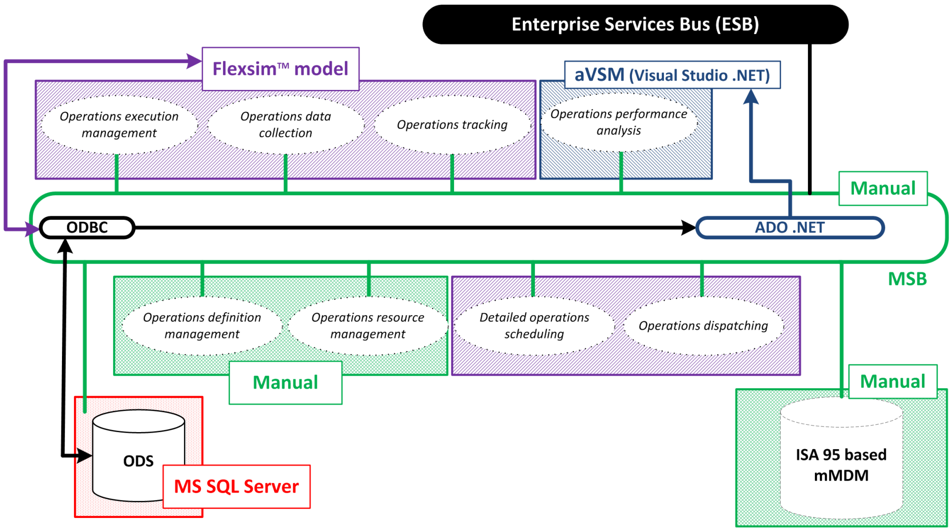



*Figure 4.2: Mapping of the components of the CharBox simulation case to the Lean MES framework*

controlled based on customer orders and inventory levels. A simple resource requirements algorithm[2] calculates a weekly production schedule. Based on the weekly schedule, the production manager sets up daily task lists for each work cell (on paper). He follows up production progress by walking around and can (e.g. every 30 minutes) prioritize a task, if necessary. The MOM analysis starts from scratch, as currently no digital support is available on the shop floor.

The change work flows, presented in section 3.4, will be illustrated on the simulation example. Figure 4.2 maps the different components of the CharBox simulation case to the proposed Lean MES framework. The ODS is represented by an MS SQL Server™database, made available through an Open Database Connectivity (ODBC) connection. The database tables are structured conform the ISA 95 models (as was presented in figure 3.11). A pilot application for aVSM is implemented in MS Visual Studio™.NET.

variation incorporated. Unforeseen circumstances; such as machine breakdowns and quality problems; are omitted from the model.

[2]A realistic schedule is not the main goal of the simulation, the generation of ISA 95 based operations data is. The manufacturing resource requirements are based on the weekly assembly task list. Customer orders are scheduled on a First Come - First Served (FCFS) basis.

The functionality of the pilot is limited to the automated construction of an eVSM template in MS Visio™format. The communication between aVSM and the ODS, that is supposed to happen through the MSB, is replaced by an ActiveX Data Objects (ADO) .NET integration. The functionality of the Flexsim™model will cover the activities *execution management*, *data collection*, *tracking*, *dispatching* and *scheduling*. The communication between the model and the ODS, that is supposed to happen through the MSB, is replaced by the ODBC connection. *Definition management* and *resource management* are performed manually by modifying the database tables in the ODS according to the changes. The change work flows, that are structured by mMDM, as presented in section 3.4, are followed manually. All required tasks within and information flows between activities are also ensured by manual actions (e.g. custom coding in the Flexsim™model or modifying database records in the ODS). The aVSM phases that will be illustrated with this simulation case were shown in table 4.1. Initially there is no MOM software support available. Therefore, the starting ODS is empty. In a first phase, MOM support will be introduced by populating the ODS through the change work flows *new product introduction* and *custom reporting*. The product family classification and selection is straightforward, as there is obviously only one, i.e. *final boxes*. After a simulation run, the historical data will enable the execution of the remaining steps: *current state mapping*, *future state mapping* and *Lean implementation*. Through a few examples, the *follow up of the Lean progress* will also be illustrated.

### 4.1.2 New product introduction

In order to support the production manager with the activities *detailed scheduling* and *dispatching* of production orders, information about the final products (product definitions) and the resources (resource definitions) must be available. This information is configured in the ODS by the activity definition management and used by the MES to provide the requested MOM support. The MES functionality is simulated by the Flexsim™model. The required change work flow, to add the new *product definitions* to the ODS, is:

1. *Information flow to resource management:* Define the new products
   (a) *Task:* Add new *material definitions* to the ODS
      i. **Final Box A**
      ii. **Final Box B**
   (b) *Task:* Add a new material class **Final Boxes** to the ODS and link the new material definitions to it.
2. *Task:* Add *product production rules* (and associated product segments) to the ODS for **Final Box A** and **Final Box B**. For each material definition, information is contained about the operation (corresponds to a process segment) sequence, batch sizes, changeover times, etc.

| Material Definition ID | Description | Material Class |
|---|---|---|
| Box A | The folded box A | Boxes |
| Box A Welded | The welded box A | Boxes |
| Box B | The folded box B | Boxes |
| Box B Welded | The welded box B | Boxes |
| Char01-40 | The punched character | Characters |
| Final Box A | The filled box A | Filled Boxes |
| Final Box A Delivered | The delivered final box A | Final Boxes |
| Final Box A Packaged | The packaged final box A | Filled Boxes |
| Final Box B | The filled box B | Filled Boxes |
| Final Box B Delivered | The delivered final box B | Final Boxes |
| Final Box B Packaged | The packaged final box B | Filled Boxes |
| Format A | The aluminum sheet format to produce box A | Sheets |
| Format B | The aluminum sheet format to produce box B | Sheets |
| Format Char | The aluminum sheet format to produce a normal character | Sheets |
| Pallet | Incoming pallet with standard sheets | Raw Materials |
| Standard | The standard format of aluminum sheets as raw material | Sheets |

*Table 4.2: The material definitions configured in the ODS for the CharBox case*

(a) *Information flow to resource management:* Add resource definitions to ODS for all material definitions (Table 4.2) and process segments (Table 4.3).

3. *Information flow to detailed scheduling/dispatching:* Based on the product definitions within the ODS, Flexsim$^{TM}$calculates a weekly production schedule that ensures the assembly of all required final boxes (i.e. production requests). A daily dispatch list - a list of segment requirements - is extracted from that production schedule and delivered to each process segment. That production sequence is considered to be visualized on a touch panel, so (priority) changes made by the production manager have immediate effect.

4. *Information flow to execution management:* Execution management is configured in the Flexsim$^{TM}$model. Each process executes its task list. Product changeovers are taken into account. Quality problems, machine breakdowns and personnel allocations are omitted in order to reduce the complexity of the model. Figure 4.3 gives a perspective view on the Flexsim$^{TM}$model that simulates the operation of MES as push control system in the AS-IS situation of the CharBox company.

5. *Information flow to performance analysis:* There is currently no MOM support implemented for analyzing purposes.

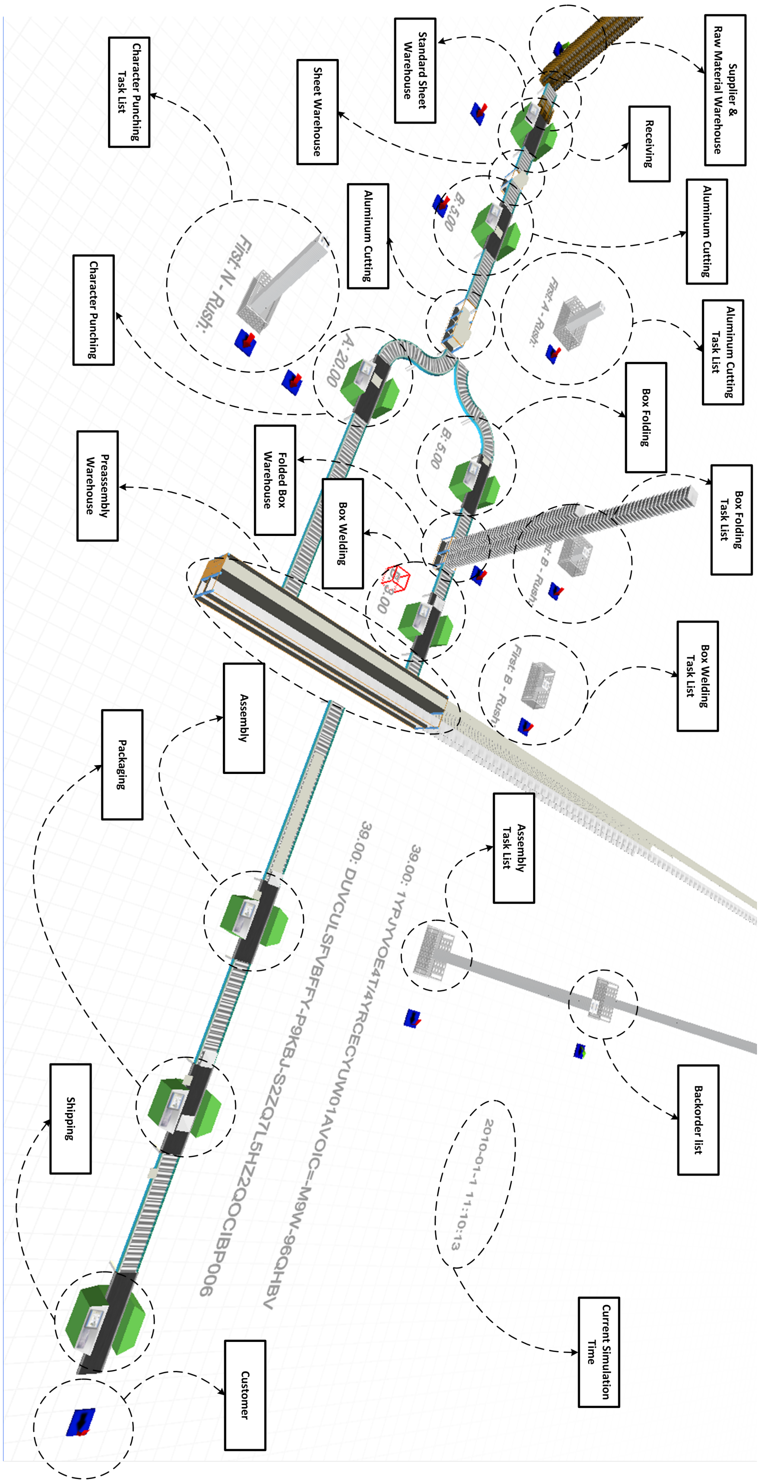



*Figure 4.3: A perspective view on the Flexsim™ model that simulates the push control system in the AS-IS situation of the CharBox company*

| Process Segment ID | Description | Published date | Type | Umbrella Process Segment |
|---|---|---|---|---|
| AS-IS CharBox | The AS-IS scenario of the CharBox case | 10/01/2010 | VSM | |
| Aluminum Cutting | The workcenter where the aluminum sheets are cut | 10/01/2010 | Production process | AS-IS CharBox |
| Assembly | The workcenter where the assembly of the final boxes takes place | 10/01/2010 | Production process | AS-IS CharBox |
| Box Folding | The workcenter where the boxes are folded | 10/01/2010 | Production process | AS-IS CharBox |
| Box Welding | The workcenter where the boxes are welded | 10/01/2010 | Production process | AS-IS CharBox |
| Character Punching | The workcenter where the characters are punched | 10/01/2010 | Production process | AS-IS CharBox |
| Folded Box Warehouse | The warehouse containing the folded boxes | 10/01/2010 | Push inventory | AS-IS CharBox |
| Packaging | The workcenter where the boxes are packaged | 10/01/2010 | Production process | AS-IS CharBox |
| Preassembly Warehouse | The warehouse containing all components to be assembled | 10/01/2010 | Push inventory | AS-IS CharBox |
| Raw Material Warehouse | The warehouse containing the pallets | 10/01/2010 | Push inventory | AS-IS CharBox |
| Receiving | The receiving process for the raw materials | 10/01/2010 | Production process | AS-IS CharBox |
| Sheet Warehouse | The warehouse containing the sized aluminum sheets | 10/01/2010 | Push inventory | AS-IS CharBox |
| Shipping | The shipping process for the final products to the customer | 10/01/2010 | Production process | AS-IS CharBox |
| Standard Sheet Warehouse | The warehouse containing the standard sheets | 10/01/2010 | Push inventory | AS-IS CharBox |

*Table 4.3: The process segment definitions configured in the ODS for the CharBox case*

### 4.1.3 Custom reporting

The activity operations performance analysis must enable the configuration for custom reporting. Based on the final information requirements, the change work flow ensures that all other activities are triggered to support the information value stream. A limited number of facts is configured to restrict the complexity and amount of work for the (manual) configuration in Flexsim$^{TM}$. But the method can easily be extended to other standard facts and even self defined information requirements.

1. *Task:* Standard VSM facts are configured to be able to document the current state map. The umbrella process segment *AS-IS CharBox* must contain the PLT, TCT and Ratio Value Added (RVA) as timeline documentation. The average daily demand and the takt time must be added as facts to the customer icon. All processes must have a data box indication for C/T and C/O. All push inventories must have an inventory time value based on the average staying time of the products.

2. *Task:* Configure data/information collection requirements

   (a) *Information flow to resource management/data collection:*

   - C/T, C/O and inventory time values are added to the process segment resource definitions. The values are calculated by standard formulas and require tracking information. Based on its information requirements, each process segment defines a *requested segment response*. The *tracking* activity will use that structure to record the necessary information.
   - PLT and TCT are calculated by standard formulas and require C/T and inventory time values.
   - RVA is calculated by a standard formula and requires PLT and TCT.
   - Customer demand (117 orders/day) and takt time (4.1 minutes) will be manually entered during analysis. The value can be validated with the actual takt time of the production process, calculated from the historical data by applying equation 4.1 to the last process segment of the value stream. The actual model output is on average 116 orders a day. That results in a takt time of 4.14 minutes.

$$\mathrm{T} = \frac{D.t_d}{\sum_{i=0}^{n-1} \sum_{j=0}^{m-1} Q_{i,j}} \tag{4.1}$$

with

$T$ = Takt time
$D$ = Number of working days
$t_d$ = Net time that is available every day (minutes)
$n$ = Number of segment responses of activity type *production run*
$m$ = Number of material produced actual objects of segment response $i$
$Q_{i,j}$ = Quantity of material produced $j$ of segment response $i$

   (b) *Information flow to definition management:* Only standard facts (as described in appendix A) are used, so no new formula definitions must be added.

   (c) *Information flow to resource management:* No new resource information is required as there are no new formulas.

   (d) *Information flow to tracking:* The activities of the production processes and inventory locations are reported by segment responses. Standard information is defined by the *requested segment response* definitions. For each process segment activity, the segment type (run & setup), start time, end time, material consumed actual and material produced actual are collected. The material

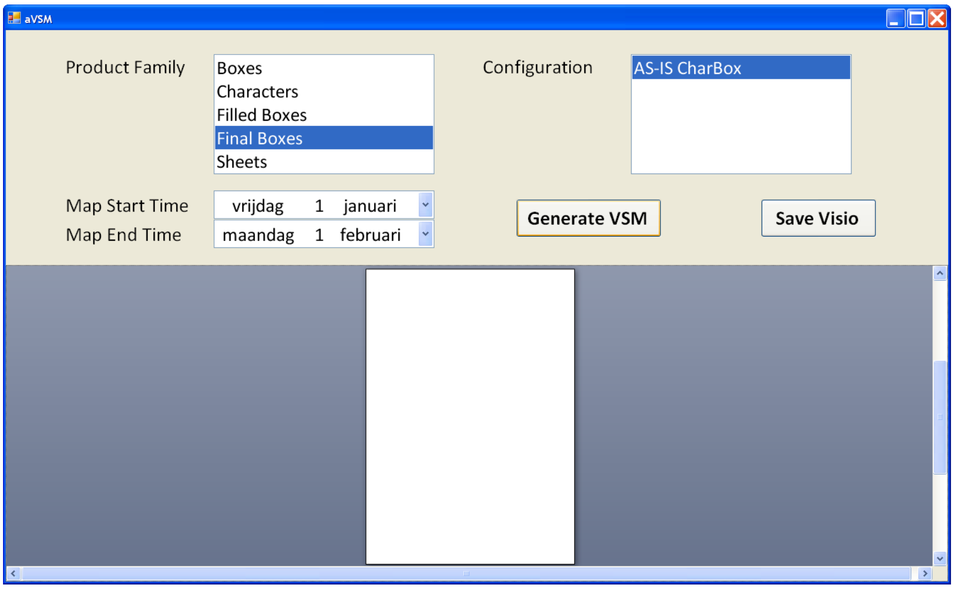



*Figure 4.4: The pilot implementation of the aVSM tool gives the opportunity to generate a MS Visio™ template of the current state map for a specified product family based on a given time frame.*

definition and the quantity of the materials consumed and produced are also defined. The tracking functionality is incorporated in the Flexsim™model. Data sources are provided by the objects of the simulation model.

3. *Information flow to execution management:* The generation of the segment responses is triggered by object events within the simulation model: onEntry, onSetupFinish, onProcessFinish, onExit, etc. Each event logs the appropriate tracking information to the ODS. In the simulation case, all activities within the material flow are recorded. The activities within the information flow could also trigger the logging of segment responses to the ODS (e.g. creation of a new weekly schedule, daily task list, purchase orders to supplier, etc.). These data would enable the drawing of the information flow on the current state map. However, as it is similar to the material flow logging, it is omitted from the analysis.

### 4.1.4 Current state mapping

After the simulation run (e.g. one month), aVSM can connect to the ODS to perform its analysis. The different steps of the analyis were listed in figure 3.6. In this simulation case, aVSM constructs a current state map template for the product family **Final Boxes**. All available information (previously configured by custom reporting) gets documented on the map. The Graphical User Interface (GUI) of the pilot implementation of the aVSM tool is shown in figure 4.4. Figure 4.5 shows the MS Visio™ file that is created by aVSM based on the CharBox simulation run.

### 4.1.5 Future state mapping & Lean implementation

Figure 4.5 shows the generated current state of a simulation run for product family **Final Boxes**. It is obviously not the intention to really optimize the CharBox case. But some changes are implemented to verify the ability to support the new situation and automatically regenerate the new VSM.

1. *Task:* The current state map of aVSM is completed by the manual analysis. Step by step, the future state map can now be configured within aVSM. Lets assume the following analysis and future state map result:

   *Figure 4.6 shows the cycle times of all processes to produce the components of one final product*[3]*. With an average customer demand of 117, the takt time is 4.1. All cycle times are lower than the takt time. In order to achieve one piece flow, the different cycle times must be similar and close to the takt time. For now, the only modification to improve line balancing is the merger of packaging and shipping into one work cell. Although character punching has a C/T way below the takt time, one piece flow is difficult because of the high C/O. The assembly operation is selected as the pacemaker process. Downstream, a FIFO lane is introduced. Upstream, kanban controlled supermarkets regulate the material flow. Only production kanbans are used. Each supermarket is located next to its downstream process, enabling physical pull of kanbans/containers.*

2. *Information flow to resource management:*

   (a) Merge process segments *packaging* and *shipping* to one process segment *packaging & shipping*.

   (b) Change *push inventory* process segments into *supermarkets/FIFO lanes*. Calculate container size and number of kanban cards as described in section 2.2. Algorithm 3 lists the calculation method. It shows that the actual average daily demand of each *material definition* at a process is extracted from the historical data in order to determine the different kanban values. The kanban lead time consists of two parts: (1) the processing time to produce the associated container; (2) the waiting time before and after processing. Processing time can be calculated based on the C/T. C/O is a part of the waiting time. For the other parts, no historical data is yet available and a standard (overestimated) time is currently used. As an example, the kanban loop configuration is described for the preassembly supermarket. The supermarket contains 42 different material

[3] In a number of cases, the value does not equal the one in figure 4.5 because it is multiplied by the average number of components that is needed for one final product. For example, a final product contains an average of 35 characters. Therefore, the C/T of 0.05 is multiplied by 35.

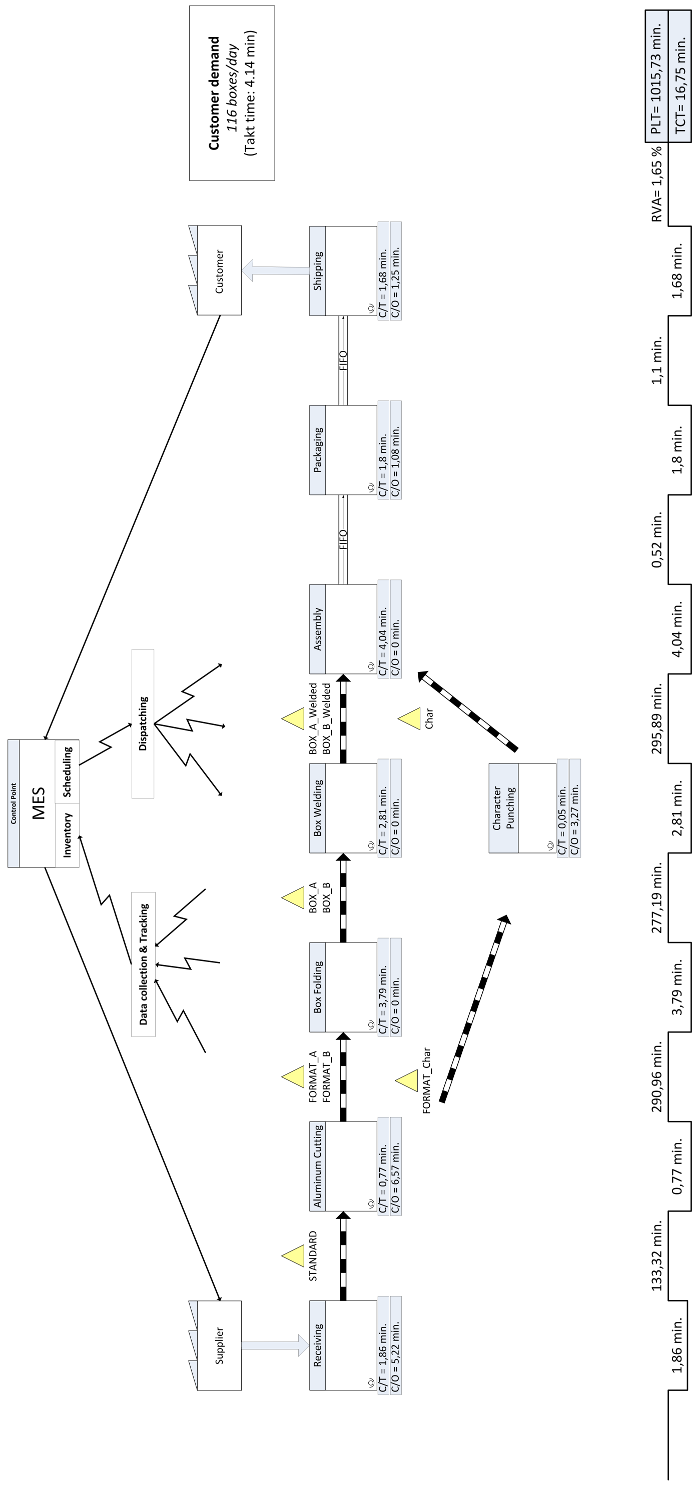



*Figure 4.5: The current state map template generated by aVSM based on a CharBox AS-IS simulation run*

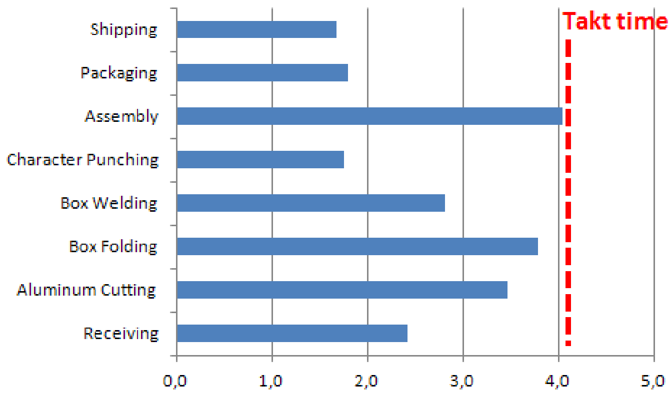



*Figure 4.6: The line balancing chart of the current state value stream*

definitions, which lead to 42 kanban types. The following average daily demands are extracted from the historical data of the AS-IS CharBox situation:

- **Box type A:** 22 boxes/day
- **Box type B:** 94 boxes/day
- **40 different character types:** 40x 100 chars/day

Algorithm 3 gives the following results for each *material definition*:

- **Box type A:** [n,k] ← [3,2]
- **Box type B:** [n,k] ← [4,10]
- **40 different character types:** 40x [n,k] ← [2,50][4]

For each kanban card, a segment requirement is added to the supermarket process segment in the ODS. Its container size, material definition, supplier and customer process segment are configured. Table 4.4 lists the kanban loop configuration for the preassembly supermarket.

As resources have changed, some other information must be updated too:

(a) *Information flow to definition management:* Modify product definitions according to the merger of packaging and shipping.

(b) *Information flow to data collection*: Modify information/data requirements for the modified process segments.

(c) *Information flow to tracking*: Modify requested segment responses

(d) *Information flow to execution management*: Modify the work flow and data triggers

[4]The container size had to be increased to 50 (instead of 10, calculated by the algorithm) to reduce the impact of the C/O. In that case, still approximately 50% of the total production time of the equipment is setup time.

**procedure** CALCULATEKANBANLOOP(*supermarket*)
  **for all** *material consumed actual* of supermarket customers **do**
    [kanbans, container] = Calculate(material definition, supermarket)
    Create the necessary segment requirements in the ODS
  **end for**
**end procedure**

**function** CALCULATE(*material definition*, *supermarket*)
  $d_{av} \leftarrow \frac{\text{total quantity of material consumed actual}}{\text{number of days}}$ ▷ *Average demand calculated from the historical data*
  $k \leftarrow 10\%.d_{av}$ ▷ *Rule of thumb to determine container size*
  $s \leftarrow 1$ ▷ *No safety factor is taken into account here*
  $t_w \leftarrow t_w$ + kanban transport time to supplier process (=0 min.) ▷ *Considering the digital nature of the transport, no time is incorporated*
  **for all** process steps from supplier to customer in the kanban loop **do**
    $t_{pc} \leftarrow t_{pc} + k.C/T$
    $t_w \leftarrow t_w$ + queue time at process till start (=60 min.) ▷ *As no historical information is yet available, a standard value is used, that can be refined later*
    $t_w \leftarrow t_w + C/O$
    $t_w \leftarrow t_w$ + transport time to next process downstream (=5 min.) ▷ *As no historical information is yet available, a standard value is used, that can be refined later*
  **end for**
  $t_{pc} \leftarrow \frac{t_{pc}}{\text{total minutes per day}}$
  $t_w \leftarrow \frac{t_w}{\text{total minutes per day}}$
  $n \leftarrow \frac{d_{av}.(t_w+t_{pc}).s}{k}$
  $n \leftarrow RoundUp(n)$ ▷ *Round up to closest integer*
**return** $[n,k]$
**end function**

*algorithm 3: Calculate the requirements for the kanban loop to regulate material flow to a supermarket*

3. *Information flow to scheduling:* Configure the modified production control. Only the pacemaker process (i.e. *Assembly*) is scheduled and maintains a standard production rate (at takt time) of the value stream. Customer orders are assembled on a FCFS basis (Figure 4.7 ❶). The packout quantity is 1, as one box is assembled at a time. That means the pitch, or the interval that an order is released to assembly, equals the takt time (i.e. 4.1 minutes).

4. *Information flow to dispatching:* Configure the new dispatching rules for all other processes. At the pacemaker process, products are pulled from upstream processes and flow through downstream processes. As an example, the dispatching rules in the kanban loops at the preassembly supermarket are described in figure 4.7. Currently, all processes are idle and all kanban cards, with associated material containers, are located at the supermarket. The *Assembly* process pulls the required components, to assemble the specific final box, from the preassembly supermarket

| Segment Requirement (kanban card) | | | Material Produced Requirement (associated container) | | |
|---|---|---|---|---|---|
| ID | Material Definition | Segment | Quantity | Unit of Measure | Location |
| BA01 | Box A | Box Folding | 2 | boxes | Preassembly Supermarket |
| BA02 | Box A | Box Folding | 2 | boxes | Preassembly Supermarket |
| BA03 | Box A | Box Folding | 2 | boxes | Preassembly Supermarket |
| BB01 | Box B | Box Folding | 10 | boxes | Preassembly Supermarket |
| BB02 | Box B | Box Folding | 10 | boxes | Preassembly Supermarket |
| BB03 | Box B | Box Folding | 10 | boxes | Preassembly Supermarket |
| BB04 | Box B | Box Folding | 10 | boxes | Preassembly Supermarket |
| C01/01 | Char01 | Character Punching | 50 | chars | Preassembly Supermarket |
| C01/02 | Char01 | Character Punching | 50 | chars | Preassembly Supermarket |
| ... | | | | | |
| C40/01 | Char40 | Character Punching | 50 | chars | Preassembly Supermarket |
| C40/02 | Char40 | Character Punching | 50 | chars | Preassembly Supermarket |

*Table 4.4: The kanban loop configuration for the preassembly supermarket in the future state map of CharBox*

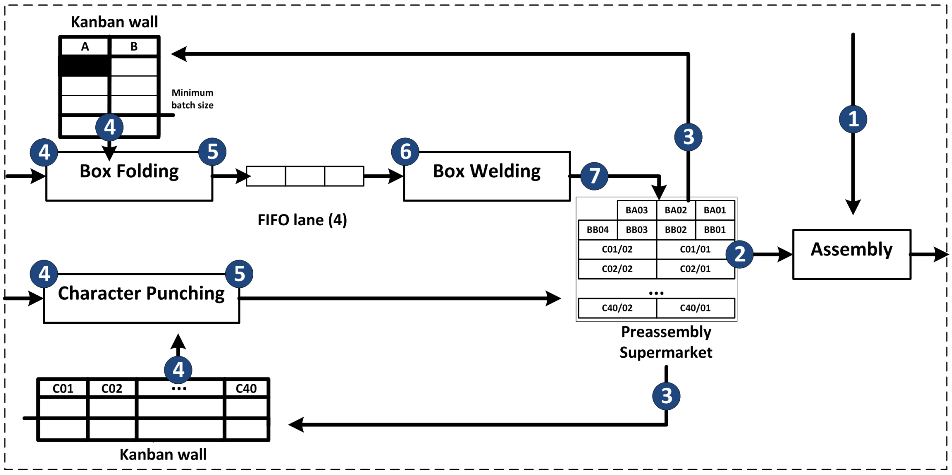



*Figure 4.7: The production control support for the preassembly supermarket in the future state of CharBox*

(❷). The released kanban cards are transported to the corresponding *supplier* process (❸). The activity execution management selects the next kanban request to be produced by the *Box Folding* and the *Character Punching* processes (❹). Box folding can only take place when an empty space is available in the downstream FIFO lane. Appendix A illustrates how the maximum FIFO value can be determined. The value is based on the maximum cycle time of the downstream process compared to the takt time. As configured in the simulation software, the Box Welding cycle time follows a combination of two normal distributions with mean values 2.5 (Box A) and 3 (Box B). The maximum value of the cycle time is 5.55 minutes. In combination with a takt time of 4.1 and a container size of 10, equation A.10

gives a maximum value of 4. In order to perform their tasks, the processes pull the required components from the supermarkets upstream (❹). When the container is produced, the kanban is moved further downstream (❺) toward its final supermarket specified by its attribute *Location*. In case of characters, they are transported to the supermarket, awaiting usage by the assembly process. The boxes wait in the FIFO lane until they are welded (❻) and transported to the supermarket (❼).

5. *Information flow to execution management:* The work flow for the new production control is initiated in the future state Flexsim$^{TM}$model. Each process produces the product definition of which it holds the most kanban cards in its kanban wall. In case of equal amount, a FIFO strategy is maintained. A FIFO lane naturally maintains a FIFO sequence at all times.

6. *Task:* Kaizen bursts are added to define and follow up CI initiatives. The number of kanbans at supermarkets (and number of places in FIFO lanes) must be further refined to achieve an optimal situation. In addition, periodic recalculations can be useful in order to react to changing conditions (e.g. variation of customer demand, production performance increase/decrease, etc.). Through SMED, an attempt can be made to reduce the changeover times of *Aluminum Cutting* and *Character Punching*. Another kaizen opportunity, is the reduction of the *Box Folding*, *Assembly* and *Packaging&Shipping* cycle times (e.g. below 3 minutes). That would enable a takt time reduction, which results in a throughput increase.

### 4.1.6 Follow up Lean progress

Assume a successful implementation of all supermarkets, FIFO's and kanban loops. Through a new simulation run, the TO-BE state of the CharBox company can be drawn, as shown in figure 4.8. This map will now be treated as the new current state. Based on the new historical data, generated by the simulation run, the previously defined kaizen bursts can be evaluated. The Lean planning system determines the road map and follows up the progress. Applied to the CharBox kaizen bursts, that gives the following sequence of PDCA cycles:

1. **C/T improvement:** A new efficient picking system speeds up assembly to a mean cycle time of 3.4 minutes. New equipment decreases the packaging time to 2.9 minutes. An improved work flow for box folding is introduced and reduces its mean cycle time to the values of box welding.

2. **Reduce C/O:** SMED is applied to aluminum cutting and character punching. All changeover times are approximately cut in half.

3. **Current state mapping:** The actual values for the C/Ts and C/Os need to be reevaluated after the process optimization efforts to quantify the improvements. The highest C/T - assembly process - is reduced to 3.4 minutes. That makes a takt time reduction possible to 3.4 minutes, with a throughput increase as result.

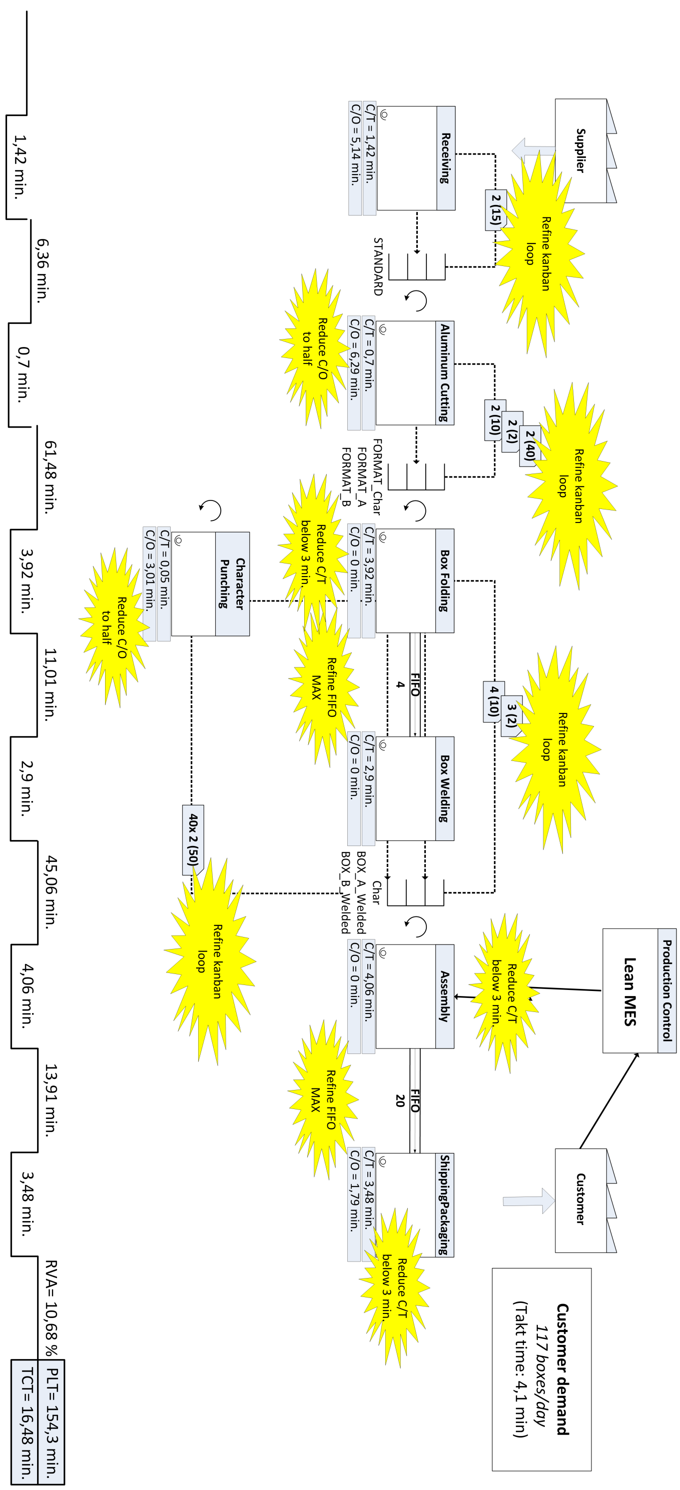



*Figure 4.8: The future state map template generated by aVSM based on a CharBox TO-BE simulation run*

4. **Refine pull control:** The FIFO values and [n,k] kanban loops are recalculated based on the new historical data. Compared to the previous calculations, a number of C/T's and C/O's are decreased, takt time is reduced, recent kanban card waiting times available, etc. However, as the methodology is identical, only the results are shown in figure 4.9.

5. **Continuous improvement towards perfection:** Figure 4.9 shows the final representation - so far - of the value stream. However - as the term CI denotes - this is no end state. New initiatives can be launched to optimize the value stream even further. For example, a pull integration with the supplier could be a next step.

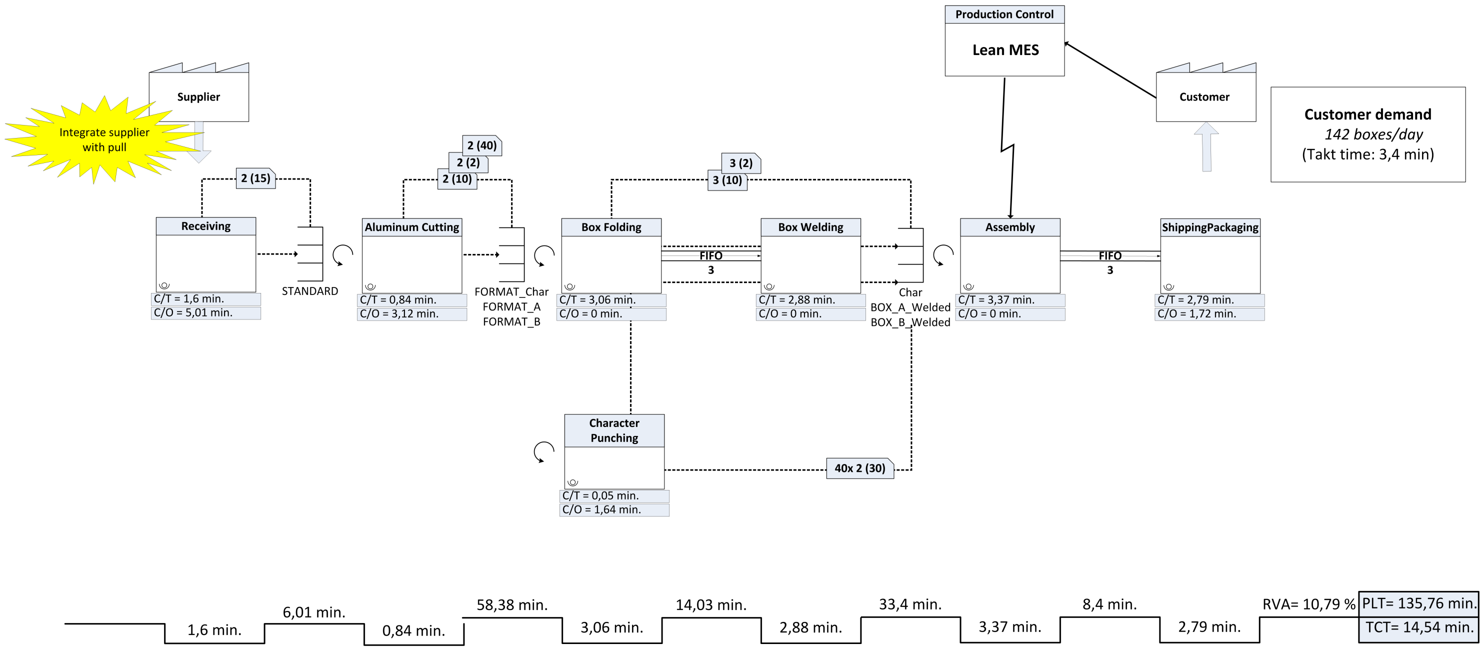



*Figure 4.9: The future state map template generated by aVSM based on a CharBox TO-BE simulation run after the different process improvements*

## 4.2 Framework validation

The lack of real test environments for MES concepts, makes it very difficult to validate the proposed approach. Real production environments (and their control) are obviously not available for this kind of testing. New concepts are usually stress tested through simulation models in order to minimize the risk at implementation. The feasibility of the Lean MES framework was verified in section 4.1. The presented match between Lean and ISA 95 terminology makes it possible to provide standard Lean support. However, how accurate the simulation model may be, it is always an abstraction of the reality and can not fully represent the complex dynamics of a production environment. In order to fully validate the Lean MES framework, its ability to support a company to discover opportunities, guide the process, achieve the goals and maintain improvements of CI initiatives must be checked. A number of factors make it hard to perform this kind of full scale validation project:

- As the framework is still in the concept stage, no mature support tools are available. For example, the pilot application of aVSM is only developed to check the concept. It does not yet contain complete functionality and flexibility to perform a full scale project.
- Due to the conceptual phase of the research, companies are not willing to allocate sufficient resources and in-house support for a full scale project. Certainly not in the current difficult economic times.

However, a number of companies were found willing to deliver historical operations data and company strategy information in support of an offline analysis. Two cases will be discussed in this section. The number of cases is limited, due to the time consuming nature of the analysis. As most of the standard tools are not yet available, a lot of manual database mutations (e.g. to map historical data to ISA 95 format) and production control functionality scripting (e.g. aVSM and simulation of future states) are necessary. Due to confidentiality issues, company names are not mentioned and some sensitive process information is omitted. The selected cases each illustrate a different setting for the application of the framework. Case A (section 4.2.1) features a big beverage manufacturing company. The batch processes are highly automated and production control has already some software support. Case B (section 4.2.2) analyses the situation of a small furniture manufacturing company. The production processes have a highly manual character and the discrete process has currently limited software support. In both cases, the usability of the framework to integrate standard Lean functionality on top of historical data is shown. However, the two cases are insufficient to really validate the approach. From the experience of both cases, the future validation requirements are set.

### 4.2.1 Case A - Beverage Manufacturing Company

Case A features a production facility of a large beverage manufacturing company. The batch processes are highly automated and production control has already considerable

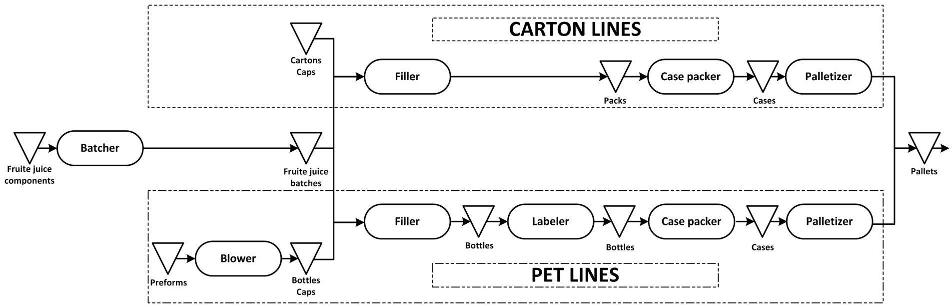



*Figure 4.10: The process flow of the beverage manufacturing company*

software support. Figure 4.11 shows the current manufacturing operations support. A batch control system contains all recipes and creates the juice mixture for each batch using a number of components. A shop floor control system supports the operators to select and execute the different batches on the packaging lines. In addition, the system enables the performance analysis of the lines. To construct the OEE figures, production operations data (e.g. unit tracking, event logging, etc.) are automatically collected. Inventory and quality information is still noted down by the operator on A3 sheets and handed in after each shift. The packaging lines are capable of producing fruit juice carton packs and Poly Ethyleen Tereftalaat (PET) bottles. The carton lines fill the packs, group them to cases and palletize them. The PET lines inflate, fill, label, package and palletize the bottles. Figure 4.10 shows both process flows. In order to improve manufacturing performance, the company states the following objectives:

1. First goal is to increase the software support on the production floor. The current control system must be expanded to support operators further in their production tasks and also incorporate quality and inventory functionality.

2. The company wants to introduce a CI mentality. The OEE calculation was a first step in the waste identification. That effort needs to be extended to the complete value stream and must involve all employees, from production manager to operator.

The above requirements are a mixture of MOM digitization (MES) and MOM optimization (Lean). The Lean MES framework structures the alignment between both. The Lean MES must impose standard work in all operational areas: production, inventory, quality and maintenance. The system must enable dynamic reporting to feed CI initiatives. The achieved improvements must be incorporated in the system, to keep it up to date and to maintain the improved way of working. This case description fits the aVSM methodology as summarized in table 4.1. The different steps in the change work flow to achieve a Lean MES within the beverage case, are marked in the overview. As the current shop floor control system will be maintained, an ISA 95 plugin is constructed to translate the MES data to the ISA 95 format. The mapping of the available historical data to the ODS can be done

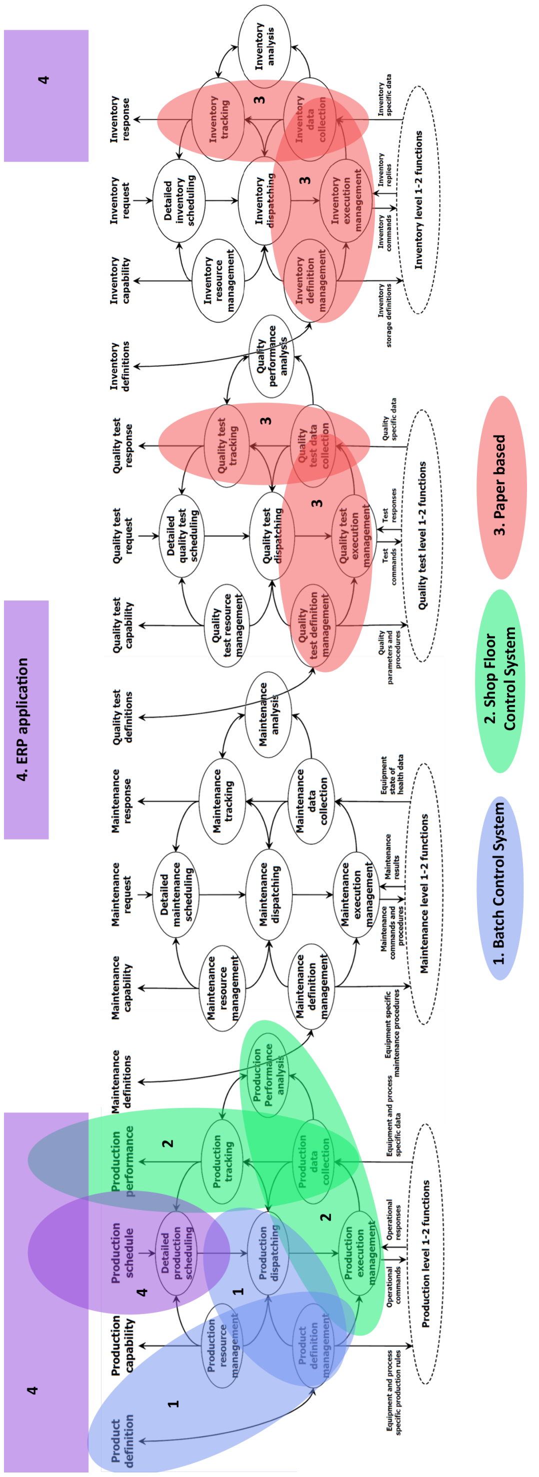



*Figure 4.11: The current manufacturing operations support within the beverage manufacturing company*

| Material Definition ID | Description | Material Class |
|---|---|---|
| Juice | A batch of fruit juice as raw material for the packaging lines | Raw Materials |
| Pack | A unit filled with juice on the carton lines | Intermediate |
| Case | A number of packs grouped together | Intermediate |
| 10115100 | JUICE TYPE1 6X1.5L | Final Beverage |
| 10115601 | JUICE TYPE2 12X1L | Final Beverage |
| 10115701 | JUICE TYPE3 12X1L | Final Beverage |
| 10115800 | JUICE TYPE4 8X25CL | Final Beverage |
| 10116900 | JUICE TYPE3 6X1.75L | Final Beverage |

*Table 4.5: A selection of the material definitions configured in the ODS for the beverage case*

| Process Segment ID | Description | Published date | Type | Umbrella Process Segment |
|---|---|---|---|---|
| FIFO_Case Packer S901 | Conveyor between the filler and the case packer of line S90-1 | 21/07/2011 | FIFO | AS-IS Beverage Level 1 |
| FIFO_Palletizer S1201 | Conveyor between the case packer and the palletizer of line S120-1 | 21/07/2011 | FIFO | AS-IS Beverage Level 1 |
| Filler H1801 | The filler of line H180-1 | 21/07/2011 | Production process | AS-IS Beverage Level 1 |
| Filler S901 | The filler of line S90-1 | 21/07/2011 | Production process | AS-IS Beverage Level 1 |
| S120-2 | Line S120-2 | 21/07/2011 | Production process | AS-IS Beverage Level 2 |
| S90-1 | Line S90-1 | 21/07/2011 | Production process | AS-IS Beverage Level 2 |

*Table 4.6: A selection of the process segments configured in the ODS for the beverage case*

continuously, at predetermined times or only when aVSM actions are actually performed. In the next paragraphs, each step will be documented in greater detail to illustrate the role of ISA 95 and to validate the Lean MES activities.

#### 4.2.1.1 Build an ISA 95 ODS

In order to apply the aVSM analysis, there are two options: (1) program all aVSM functionality in the existing shop floor system to cope with the company-specific data; (2) use the standard aVSM functionality and translate the company-specific data to the ISA 95 format. The second option is obviously more feasible. The ISA 95 ODS is the common database for all activities of the featured Lean MES. That database must contain all necessary master and operations data in ISA 95 format in order to support aVSM. This information is currently contained in the shop floor control system. The information is structured in a company-specific manner with a complex relational database (140+ tables). First, all material definitions (Table 4.5) and process segments (Table 4.6) are manually added to the ODS. In a next step, the information requirements are set for each process segment. The following information will be mapped:

- Process C/T: The average time difference between the production of two good products. That is the monitored production time divided by the number of products produced.
- Process C/O: The average change-over time between production batches.
- Process Uptime (U/T): The uptime of the process. The percentage equals the monitored production time divided by the total available time. The more operational stops and equipment failures, the lower the percentage.
- Process defects: The percentage of defects is the ratio of scrap over total products produced[5].
- Value stream PLT: Sum of all process cycle times and inventory waiting times of the critical path of the value stream. Dividing the C/T by the U/T and defects percentages includes the non-value adding factors.
- Value stream TCT: Sum of all value added cycle times of the critical path of the value stream.
- Value stream RVA: Ratio of the total value added time on the total product lead time ($\frac{TCT}{PLT}$).

The above configuration by custom reporting, will enforce the requirements for the ISA 95 plugin for the shop floor control system. For each segment activity, the required operations data are structured in a *requested segment response*. Its required attributes are:

- *ID*
- *Process segment:* Where the activity took place
- *Actual start time:* Start time of the batch logging at the process segment
- *Actual end time:* End time of the batch logging at the process segment
- **Materials consumed actual**
  - *Material definition:* What is consumed in that time interval?
  - *Quantity:* How many?
  - *Quantity unit of measure*
- **Materials produced actual**
  - *Material definition:* What is produced in that time interval?
  - *Quantity:* How many?

[5]The total number of products consumed by the process will be used to determine what should be produced. The scrap is identified by the difference between the total products consumed and total (good) products produced.

  - *Quantity unit of measure*
  - *Location:* Where is the material now?

- **Production data**
  - *Segment type:* What kind of activity: Setup, Run, etc.?
  - *Monitored Production Time:* The total actual production time at the process segment. This equals the total time (from actual start time to actual end time) minus all operational stops and equipment failures.

The shop floor control system holds information about the events (equipment failures, change-overs, operational stops, etc.) and counter logging (number of packs produced, number of liters juice consumed, etc.) of the batches on the different process segments. A custom VB.NET application transforms a subset of the available historical data to the ISA 95 format.

#### 4.2.1.2 Identify product families

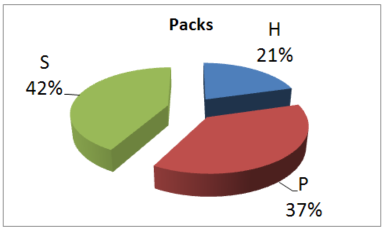
Currently, all final products are contained in the material class *Final beverage*. To enable a correct mapping of the value streams, the products must be subdivided into different product families. A product matrix is constructed to determine the commonalities between the routings of the different final products. The available tracking data determine for each process segment if it was used to produce a particular product type. Each material definition is represented by a vector in process segment utilization space. The value '1' indicates the (possible) use of the process segment to produce the final product, otherwise the value is '0'. The algorithm *$k$-means clustering* - using the Mahalanobis distance - is applied to the resulting matrix for $k$ varying from 1 to 10 product families[6] to group the material definitions by their similarity. The best clustering is reached with 3 product families:

1. **S-Family:** 71 different material definitions produced on carton lines S90-1&2 and S120-1&2. The final products are cases of 6 or 12 carton packs of 1 liter (only occasionally 0.75 l).
2. **P-Family:** 35 different material definitions produced on PET lines 1&2. The final products are cases of 8 (and sometimes 32 or 48) PET bottles of 0.25 or 0.33 cl.
3. **H-Family:** 25 different material definitions produced on carton lines H90-1&2 and H180-1&2. The final products are cases of 6 carton packs of 1.5, 1.75 or 2 liter.

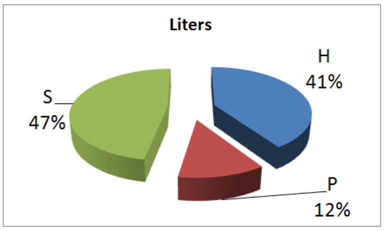
#### 4.2.1.3 Select initial exercise

The product family with the most potential is selected. As decision criteria, the total produced quantity of the product families is used. The pie charts in figure 4.12 show the

[6] There are 10 different production line names in the database of the shop floor control system.




(a) Amount of packs




(b) Amount of liters

*Figure 4.12: The share of each product family in total amount of final products*

share of each product family in the amount of packs and liters produced. In both cases, the product family *S-Family* is the winner.

#### 4.2.1.4 Current state mapping

Figure 4.13 shows the resulting current state map template of the beverage manufacturing company for the product family *S-Family*. Three parallel lines produce the same product family. The current state map generated by aVSM points out a number of inconsistencies[7] and missing values[8]. It is clearly a test database, as an evolution is noticeable in the amount of data that is available over time.

During the first improvement cycle, the *data collection* and *tracking* requirements within MES should be critically reviewed and restructured to provide the required information. Because of the offline nature of the analysis, execution of further aVSM steps is currently not possible. There is no opportunity to take a new snapshot of the ODS after the first improvement.

### 4.2.2 Case B - Furniture Manufacturing Company

Case B is performed within a small (< 50 employees) furniture manufacturing company, producing leather couches by Make To Order (MTO) strategy. The company maintains a high product variety, but all products follow, more or less, the same process flow. Figure 4.14 shows the process flow of the AS-IS situation. The *Cutting* process cuts the leather conform the product templates. The leather pieces are stitched together by the *Stitching* process to form one cover. The frames of the couches are prepared by the *Singeling* process. Foam rubber is sticked to the frames by the *Sticking* process. Pillows are prepared by the *Stiching* process. *Covering* assembles the final products by wrapping the cover around the final frame and placing the final pillows and other accessories. At the end,

[7]The filler process segments have negative values for defects. That means that the overall output count exceeds the input count. So, more packs are produced than liters juice and cartons are consumed. As that is physically not possible, the database must contain wrong data.

[8]There is no information available for the input count and the changeover times of the case packer and palletizer processes.

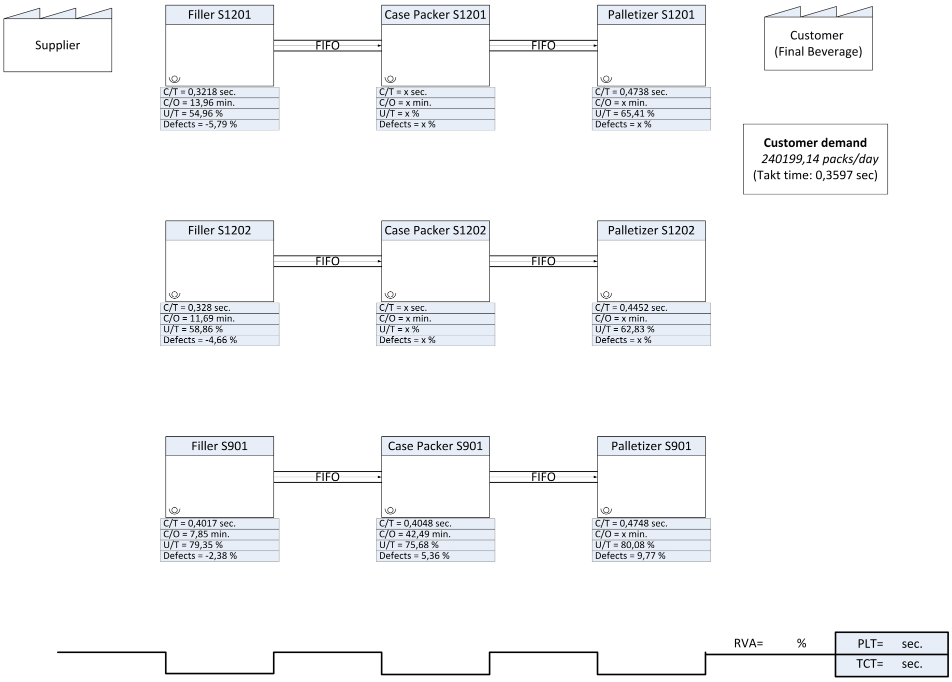



*Figure 4.13: The current state map of the beverage manufacturing company on equipment level*

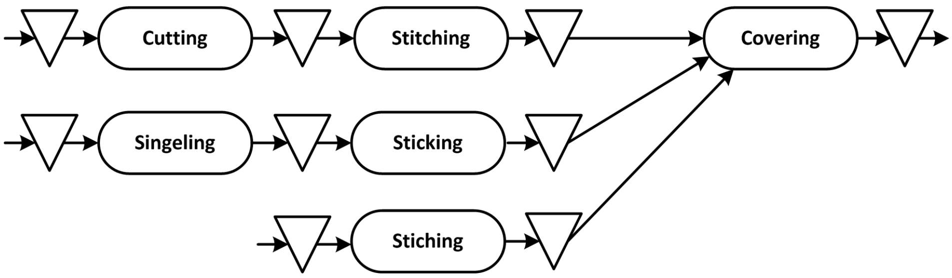



*Figure 4.14: The process flow of the furniture manufacturing company*

final products are grouped to production orders and shipped to the customers. In between all processes, buffer locations are available to stock the WIP. All transports and production activities are done manually (in some cases supported by equipment) by operators. There is (limited) production support by software tools in the AS-IS situation, so the case is treated as a brownfield project. The current manufacturing operations support is shown in figure 4.15 and consists of:

- MS Excel™: The production manager creates a production schedule once a week. Internal quality problems are kept in another file.

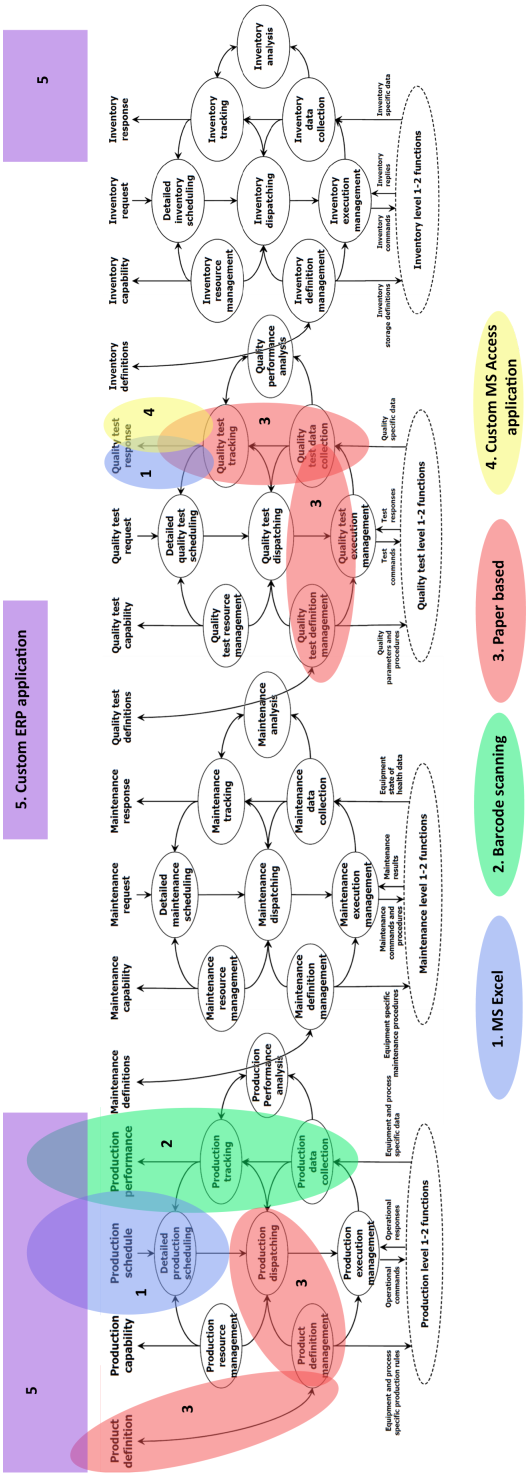



*Figure 4.15: The current manufacturing operations support within the furniture manufacturing company*

- Barcode scanning: The start of each activity on an order by an employee is recorded through barcode scanning. Two times a day, this information is synchronized with the ERP system.
- Paper based: Work orders and product definitions are distributed by the production manager based on the schedule. Once or twice a day the progress is measured by revisiting each work center. Quality checks are indicated on the work orders and results are written down by the employees.
- MS Access$^{TM}$: Customer complaints are logged into a custom application.
- Custom ERP system: Responsible for accounting, procurement of raw materials, order processing, etc.

Most of the above functionality was introduced in the past to be able to calculate some KPI values. Each month the manager retrieves information from the different systems and calculates the following values using MS Excel$^{TM}$:

- Number of seats produced
- Efficiency of employees and work centers
- Leather consumed
- Number of internal reparations
- Number of external complaints

Based on the scanning results, the theoretical lead time for each production step is regularly modified (manually) within ERP. This is done to actualize cost calculation for the different models and increase planning accuracy. The company faces the following main problems:

1. The **MOM support** is currently not efficient. The paper and spreadsheet based communication is time consuming and error prone. Useful operations data are collected through the barcode system. However, the full potential of the data is not used. To calculate monthly KPI values, the ERP system exports data to an MS Excel$^{TM}$sheet. The labor intensity of the calculations, results in an underutilization of the available information. A paperless and fully integrated MES system could deliver a more effective and more efficient solution. In addition, the new system could uncover valuable information that is not visible at first sight. In the future, a WMS will also be implemented to control the stock of raw materials. However, inventory control falls out of scope for this case study.
2. The company wants to introduce a CI mentality. A first step would be the optimization of the value stream performance by **reducing the WIP** (and by doing so, reducing the PLT) and creating a higher manufacturing visibility and efficiency. A

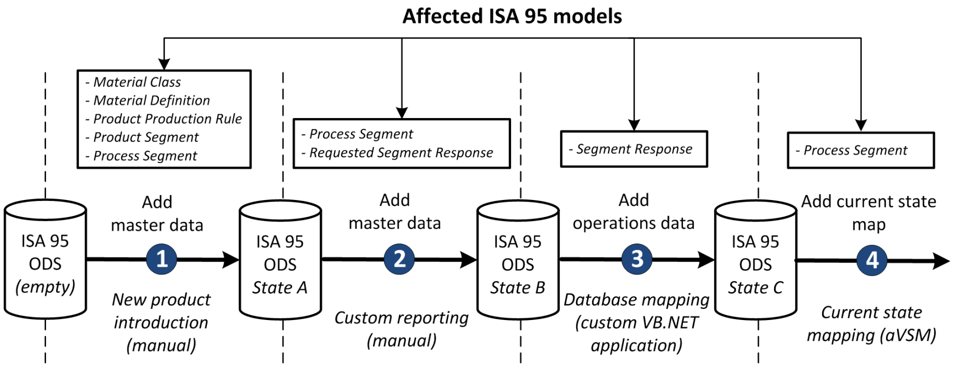



*Figure 4.16: The different steps in the database mapping to populate the ODS in the furniture case*

high WIP level is usually maintained to hide inefficiencies. By systematically lowering the WIP level, problems are revealed and can be tackled. The company wants to perform a Lean transformation to support those goals.

The above requirements are a mixture of MOM digitization (MES) and MOM optimization (Lean). The Lean MES framework structures the alignment between both. In a first phase, MOM support (currently paper and spreadsheet based) must be incorporated by a paperless MES system. The production manager gets the released orders from ERP and must be able to launch orders on the shop floor. Each work center could have a touch panel with an overview of its task list of waiting production orders. Through simple screen actions, employees can indicate which order they start. They get electronic information about the required materials and actions. When finished they are guided through some quality checks and can release the order, which will then be sent to the next step. The system contains a lot of tracking information, that will be used to calculate the monthly desired KPI values for the manager. In a second phase, Lean functionality can be integrated in MES to support the Lean transformation towards the future state and facilitate future CI initiatives. This case description fits the aVSM methodology as summarized in table 4.1. The different steps in the change work flow to achieve a Lean MES within the furniture case, are marked in the overview. In the next paragraphs, each step will be documented in greater detail to illustrate the role of ISA 95 and to validate the Lean MES activities.

#### 4.2.2.1 Build an ISA 95 ODS

The ODS is the common database for all activities of the featured Lean MES. That database must contain all master data and operations data in ISA 95 format. Figure 4.16 shows how the ODS is set up. At the start, an empty ISA 95 database structure is available (as previously shown in figure 3.11). In support of production control, master data are added (❶). All final products have a similar product work flow and are grouped by

| Material Definition ID | Description | Material Class |
|---|---|---|
| Cover | The leather cover of the couch | Intermediate |
| Cutted Leather | Pieces of cutted leather based on the product templates | Intermediate |
| Final Article | A final product | Furniture |
| Final Frame | Frame that is ready to be covered | Intermediate |
| Final Order | Combination of the final articles for one customer | Furniture Combination |
| Final Pillow | A finished pillow | Intermediate |
| Foam Rubber | Foam rubber and pillow materials | Raw Materials |
| Frame | A rough frame | Raw Materials |
| Leather | Leather sheets | Raw Materials |
| Singeled Frame | Frame with webbings | Intermediate |

*Table 4.7: The material definitions configured in the ODS for the furniture case*

the product family (i.e. material class) *Furniture*. For the purpose of this analysis, one material definition (= *Final Article*) and associated product production rule for all final products will be sufficient. The different materials in the value stream are defined by additional material definitions. Table 4.7 lists the different material definitions for the furniture case. The product production rule links the different processes to produce the final product by product segments. The different segments of the value stream are given in table 4.8. At all work cells, production begins at 8 a.m. and ends at 4:18 p.m., with a lunch break from 12 a.m. till 1 p.m. That means that each process segment capability equals 438 minutes.
In a next step, the information requirements are set for each operation (i.e. process segment) (❷). Change work flows are triggered in order to enable the following facts:

1. Process Time (P/T): The average raw processing time for a product by the process. This information can be extracted from the scan times for each product and also incorporates in-process inventory times.

2. Process Operators: The average number of operators in the work cell. Some operators can move work cells to balance the flow. That is why the operator count is a decimal value and not an integer. Each scan is associated with an operator action and can be used to determine the average number of operators.

3. Process C/T: The average time difference between the production of two good products. Can be approximated by dividing the average value added process time by the number of operators.

4. Process RVA: The percentage of the P/T that value is really added to the product. Due to waiting times for equipment (e.g. special stitching machine or certified operator), material availability, priority changes, etc. products do not always flow through the process. The more waiting time, the lower the percentage. This is

| Process Segment ID | Description | Published date | Type | Umbrella Process Segment |
|---|---|---|---|---|
| AS-IS Furniture | The current state map of the furniture case | 10/02/2011 | VSM | |
| Cover Warehouse | In-process buffer for covers | 10/02/2011 | Push inventory | AS-IS Furniture |
| Covering | Process where frames are covered | 10/02/2011 | Production process | AS-IS Furniture |
| Cutted Leather Warehouse | In-process buffer for cutted leather | 10/02/2011 | Push inventory | AS-IS Furniture |
| Cutting | Process where pieces of leather are cut | 10/02/2011 | Production process | AS-IS Furniture |
| Final Frame Warehouse | In-process buffer for final frames | 10/02/2011 | Push inventory | AS-IS Furniture |
| Final Pillow Warehouse | In-process buffer for final pillows | 10/02/2011 | Push inventory | AS-IS Furniture |
| Final Warehouse | Warehouse containing the final articles | 10/02/2011 | Push inventory | AS-IS Furniture |
| Frame Warehouse | Raw material warehouse for frames from supplier | 10/02/2011 | Push inventory | AS-IS Furniture |
| Leather Warehouse | Raw material warehouse for leather from supplier | 10/02/2011 | Push inventory | AS-IS Furniture |
| Singeled Frame Warehouse | In-process buffer for singeled frames | 10/02/2011 | Push inventory | AS-IS Furniture |
| Singeling | The singeling process | 10/02/2011 | Production process | AS-IS Furniture |
| Stiching | The stiching process | 10/02/2011 | Production process | AS-IS Furniture |
| Sticking | The sticking process | 10/02/2011 | Production process | AS-IS Furniture |
| Stitching | Process where the leather is stitched to covers | 10/02/2011 | Production process | AS-IS Furniture |

*Table 4.8: The process segment definitions configured in the ODS for the furniture case*

calculated by the ratio of the average sum of all value added production activity durations and the average staying time of the products in the process.

5. Inventory time values: Average staying time of the materials in the warehouses.
6. Value stream PLT: Sum of all process cycle times and inventory waiting times of the critical path of the value stream.
7. Value stream TCT: Sum of all value added times of the critical path of the value stream. Calculated by adding all value added portions of the process cycle times.
8. Value stream RVA: Ratio of the total value added time on the total product lead time ($\frac{TCT}{PLT}$).

The above configuration by custom reporting, will enforce the requirements for the tracking activity. For each segment activity, the required operations data are structured in a *requested segment response*. Its required attributes are:

- *ID*

- *Process segment:* Where the activity took place
- *Actual start time:* First 'start activity' scan time in the work cell
- *Actual end time:* Last 'end activity' scan time in the work cell
- **Materials consumed actual**
  - *Material definition:* What is consumed?
  - *Quantity:* How many?
  - *Quantity unit of measure*
- **Materials produced actual**
  - *Material definition:* What is produced?
  - *Quantity:* How many?
  - *Quantity unit of measure*
  - *Location:* Where is the material now?
- **Production data**
  - *Segment type:* What kind of activity: Setup, Run, etc.?
  - *VATime:* Sum of all operation times for that article in the work cell

Finally, the available historical operations data are added to the ODS (❸). Currently, operators scan information at the beginning of each operation: operator ID, operation ID, final product ID, order ID, date and duration. The start of a new operation means the end of the previous one. The data are available in the ERP system, but are unstructured and currently not fully used. Occasionally, data are exported to MS Excel™to perform an offline analysis. Historical data of six months (January 2010 - June 2010) of production are available and will be integrated within the ODS for the initial analysis. During the time frame of the analysis, 786 customer orders ($\subset$ *Furniture combination*) or 1747 articles were launched in production. Each order is a combination of one or more of the 390 different final products ($\subset$ *Furniture*). As the new MES will replace current MOM support, a one-time database mapping is performed to populate the ODS. A custom VB.NET application automatically generates the *segment responses* based on the *requested segment response* structure.

Support for production control (detailed scheduling, dispatching, execution management, data collection & tracking) will not be configured at this time. It is not useful as the situation will change anyway. After the current state map analysis, the new production control will be introduced.

#### 4.2.2.2 Current state mapping

The standard aVSM tool connects to the ODS to generate a current state map (Figure 4.16 ❹). Figure 4.17 shows the resulting current state map template (MS Visio™file) of the furniture manufacturing company for the product family *Furniture Combination* (i.e. final customer orders). This template can be further completed by a manual exercise. In this particular case, additional information will be gathered - when needed - during the future state mapping exercise.

#### 4.2.2.3 Future state mapping

Based on the available parts of the current state map, a number of remarks can be made, that must be taken into account when drawing the future state of MOM:

1. **No information available about the *Singeling* process:** The distance to the current barcode scan system is too far and the system is therefore not used.
2. **Limited information available about the *Stiching* and *Sticking* process:** Data can not always be linked with a particular order due to incomplete data.
3. **No distinction between setup and process time:** Operators only scan once for each article. There is no information available about C/O. Examples of setup activities are: fetch product templates for cutting, collect raw materials from warehouses, change wire color for stitching, etc.
4. **Inaccurate time values:** For each operation, only the date and the duration is logged. The historical data do not contain exact start and end times on that day. That results in an overestimation of the process times and - as a consequence - a lower process RVA than in reality.

A query on the historical data shows that during 120 working days of 438 minutes, 1747 final articles are transported to the customers at the end of the value stream. That results in a production rhythm of 14.56 final articles every day or a takt time of one article every 30.08 minutes. The calculated cycle times (29.76 - 30.24 - 30.38) indicate a fairly balanced process flow. That is the result of efficient operator allocations. A number of operators are capable of performing multiple tasks and are shifted around as result of work load changes. However, the low process RVA[9] illustrates an inefficient work cell organization. A lot of waiting times exist in between actions in a work cell. For example, the cutting process has a RVA of 8.33%. That means that only 8.33% of the staying time, the article is actually being processed in the work cell. The historical data contain multiple scan actions for the cutting operation of the article, with waiting times in between. These breaks in operation can be caused by priority changes, rush orders, material shortages, waiting times for capable operator or equipment, etc. As a result, work cells maintain a

[9]As mentioned earlier, the inaccurate time values result in a lower RVA value than in reality. However, a quick look at the historical data indicates that the low value is mainly caused by the waiting times between work cell activities.

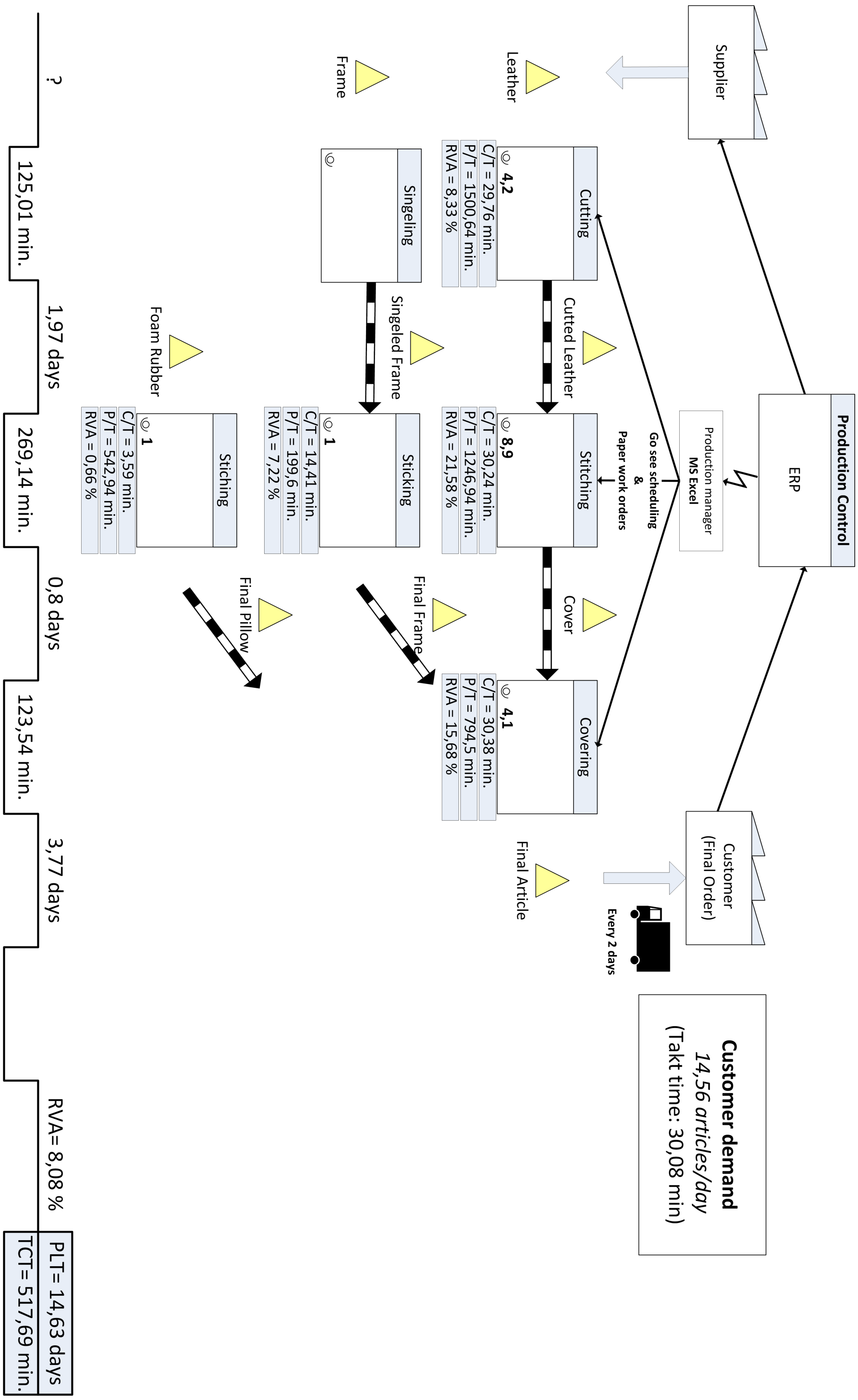



*Figure 4.17: The current state map template generated by aVSM based on the available historical data of the furniture manufacturing company*

high WIP and articles do not flow in a FIFO manner towards the end of the value stream. An ISA 95 based approach to determine the WIP evolution of a process segment in a discrete process[10] is given by algorithm 4. Figure 4.18 shows the WIP diagram of the different process segments of the main value stream of the furniture manufacturing company for day 10 till day 100. By summing all values (push inventory values included), the total amount of WIP can be determined. That level highly fluctuates. In het beginning the average is around 140 articles and towards the holiday it drops to around 100. Weekends and holidays are represented by horizontal lines. The inventory level changes of the final warehouse roughly visualize the transport frequency to the customers. Compared to the number of operators, each work cell displays a high level of WIP.

```
procedure WORKINPROCESS(process segment, time unit)   ▷ Time unit options are: month, week, day, hour, min
    for all segment responses i corresponding to the process segment do
        S[i] ← Time value of Actual Start Time of segment response i
        E[i] ← Time value of Actual End Time of segment response i
        IN[S[i]] ← IN[S[i]] + 1
        OUT[E[i]] ← OUT[E[i]] + 1
    end for
    WIP[0] ← Initial WIP value                          ▷ If known
    for all Time values j do
        WIP[j] = WIP[j-1] + IN[j] - OUT[j]
    end for
    Plot WIP in function of time values
end procedure
```

*algorithm 4: Generate and visualize the WIP evolution of a process segment for a chosen time unit*

In order to reduce the WIP level (and its variation), the use of CONWIP (see section 3.3) is introduced in the future state. To achieve a constant WIP, finishing a production order triggers the release of a new one. Considering Littles' Law, a WIP reduction results in a PLT decrease. In addition, by reducing the number of CONWIP cards, problems get revealed. For example, a question can be: Why are processes maintaining so much WIP? By investigating the underlying causes, flow can be optimized and WIP even further reduced. The CONWIP system eliminates the overall production scheduling and introduces a distributed production control. Each work cell can determine its own optimal priority rule to select the order sequence. The operation of the CONWIP system in ISA 95 terminology is described in appendix A. In order to test the configuration of the future state, a simulation model is constructed in Flexsim™. The actual production run during the six months is replayed using the historical data. The duration of each work cell operation on an article is known. The influence of the CONWIP control and local priority rules in the

[10]The given approach is only valid for a discrete process, where the number of discrete products can be counted as WIP. In the job shop environment of the furniture manufacturing case, the WIP is determined by the sum of all articles (already started, but not finished) within the considered work cell.

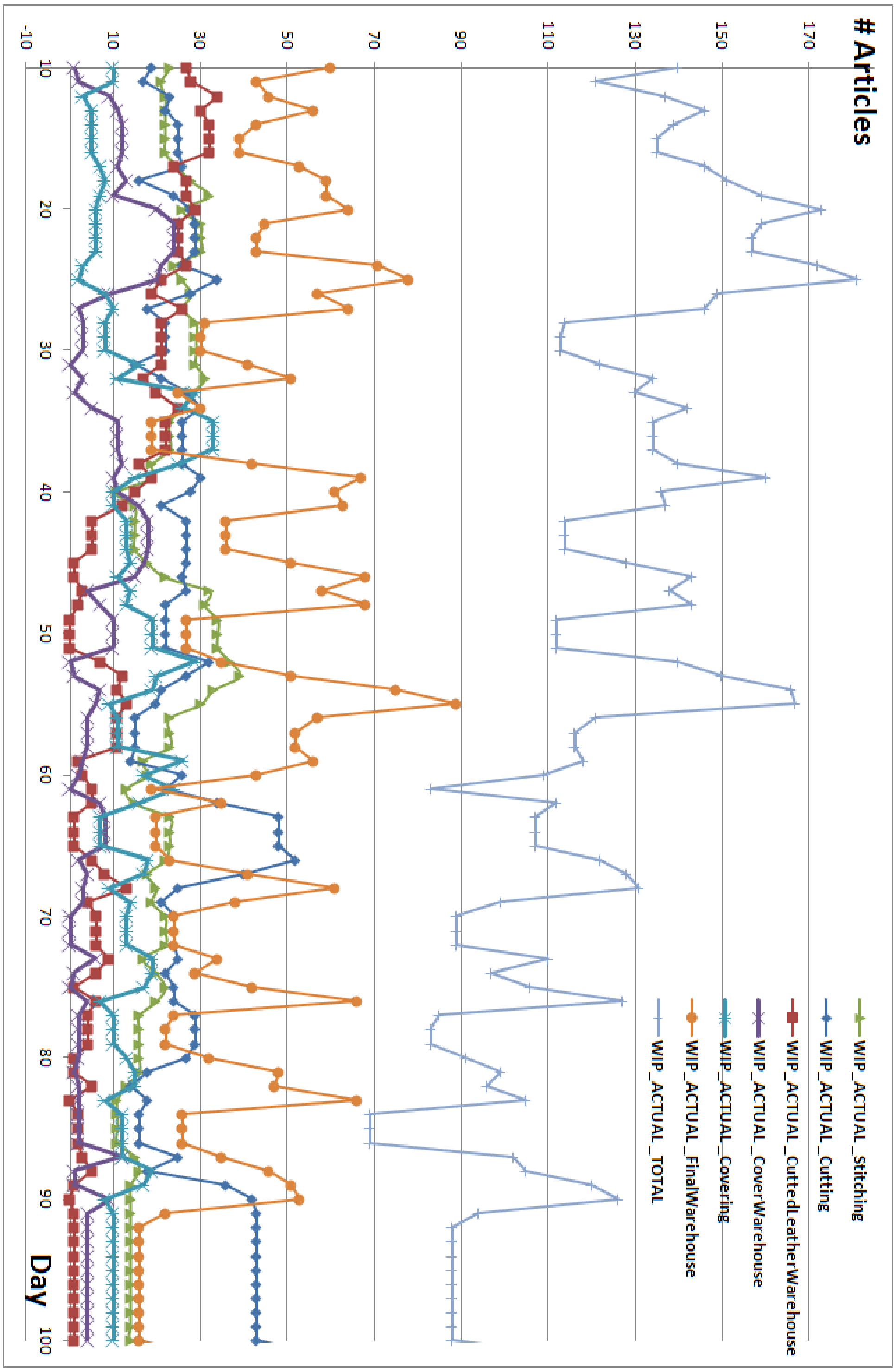



*Figure 4.18: A WIP plot illustrating the daily changes in the WIP of each process segment in the AS-IS situation of the Furniture case*

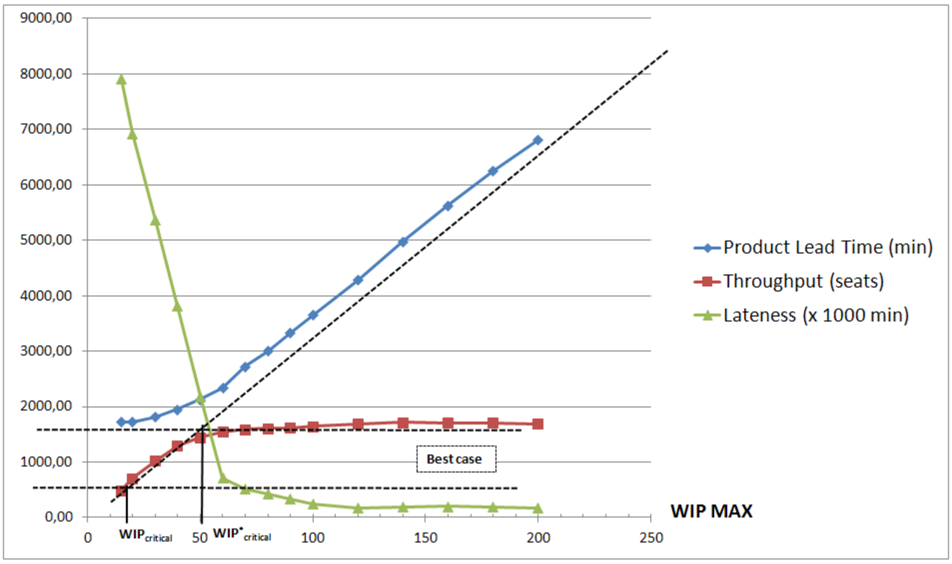



*Figure 4.19: Effect of the future state WIP reduction determined by the simulation model*

future state are evaluated. To compare the performance with the current situation, three standard KPIs are calculated: throughput, lateness and PLT.

1. **Effect of the CONWIP level:** The results of the simulation suggest that the CONWIP level is first set to 100 articles. Figure 4.19 shows that reducing the WIP to that constant level does not have a significant influence on throughput and lateness, but has a drastic decrease of the average PLT. Recall from the basic Little Law that there exists a critical WIP level that is the minimum WIP level in which the maximum production rate is attained (Hopp and Roof, 1998). The bottleneck is the process with the highest utilization. As operators are frequently shifted around, that process is difficult to determine in this case. However, on average the *Covering* process has the highest utilization. Its throughput rate is 1 article every 30.38 minutes. The total processing time equals 517.69 minutes. Using equation 4.2, that results in a critical WIP ($WIP_{critical}$) of 17 articles. Figure 4.19 shows how - in the best case - the PLT starts to increase around that WIP level. In case of a WIP level of 1, the PLT should equal the total processing time of 493.55 minutes. Because the transport of the articles to the customers is also incorporated in the CONWIP loop, the real curve stays way above this value. Each article in the final warehouse, has to wait for: (1) the next transport and (2) the other articles of the same order[11]. Incorporating these extra processing times results in an adjusted critical WIP value

[11] Running the simulation with a CONWIP level below 15 is useless. The simulation stops because all articles in the CONWIP loop keep waiting in the final warehouse. As no articles leave the system, no new ones can enter, resulting in a deadlock. That could be avoided by adding all articles of an order at once.

of 50 ($WIP^*_{critical}$). A starting WIP level of 100 is proposed, considering the lateness and throughput deterioration below that level. But there is clearly room for future optimization efforts to decrease the WIP level even further. Step by step, through PDCA cycles, changes can be introduced to achieve that WIP reduction. Figure 4.20 shows the WIP plot illustrating the changes in the WIP level of all process segments in the TO-BE situation with a CONWIP level of 100 articles. The average WIP maintained by the different processes is clearly reduced, compared to the AS-IS situation. As the WIP piles up in front of the covering process, it is identified as the bottleneck. That was not visible in the WIP diagram of the AS-IS situation, as operators are dynamically moved to the bottleneck to balance the value stream. As no specific information is available about this practice, the simulation model only incorporates one shift in operator allocations. That takes place after the holiday (Day 100 in Figure 4.18 and day 65 in Figure 4.20). From that moment the bottleneck shifts from the covering process to the stitching process.

$$W_0 = r_b.T_0 \tag{4.2}$$

with

$W_0$ = Critical WIP level
$T_0$ = Total processing time
$r_b$ = Bottleneck rate

2. **Effect of the realtime production control system delivered by the MES:** The *process time MAX* parameter indicates the effect of priority changes in each work cell. For example, a value of 219 minutes means that an operator checks every half day if there are other articles waiting with a higher priority. If there are, then the operator puts the current article aside and shifts production to the other article. The *process time MAX* parameter is determined by the time constant of production control. In the current situation, the production manager walks the shop floor 1 or 2 times a day in order to follow up production progress. By comparing the findings with the original schedule, priority changes can be made. On average, every 328 minutes an operator can be 'forced' to change to a prioritized article, if necessary. A more frequent change would be possible, if a visual system (e.g. touch panel) would be available at each work cell indicating the production progress. Visual management tools (e.g. list with different colors indicating priority) can trigger the operator to maintain an optimal sequence of articles at all times. For example, a maximum process time of 30 minutes means that an operator checks every half an hour if another article has a higher priority. Figure 4.21 illustrates the effect of the realtime production control system in combination with the CONWIP

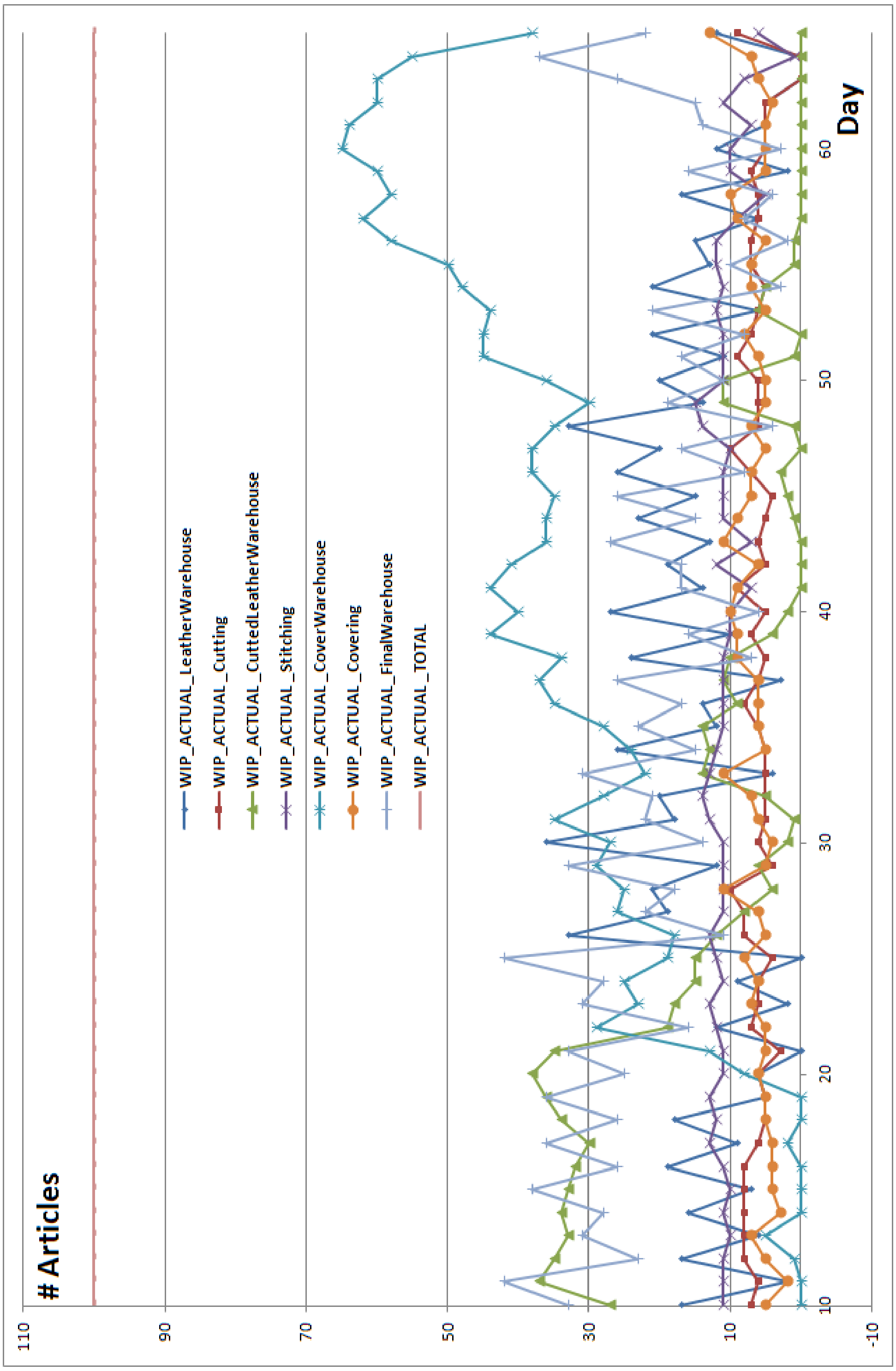



*Figure 4.20: A WIP plot illustrating the daily changes in the WIP of each process segment in the TO-BE situation with a CONWIP level of 100 articles*

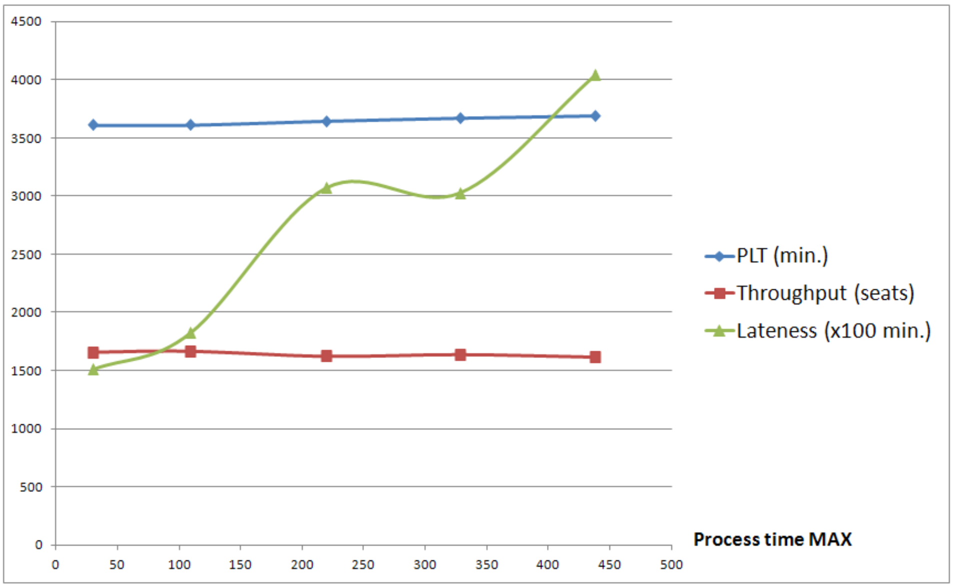



*Figure 4.21: Effect of the realtime production control of MES determined by the simulation model*

system of level 100. Increasing the control frequency has no significant influence on throughput and average PLT. However, it does result in a reduction of the lateness of articles.

3. **Effect of the priority rules:** A number of (combinations of) priority rules were tested:

    0. FIFO (+ Earliest Due Date (EDD))
    1. EDD (+ FIFO)
    2. Critical ratio
    3. Work ratio: Select article based on the level of stock in the downstream buffer. When low, select the article with the lowest ratio of $\frac{\text{work at this work cell}}{\text{work at the next work cell}}$. When high, select the highest ratio.
    4. Shortest Operation Time (SOT)
    5. Prioritize articles of orders that have already articles waiting for transport (+ EDD)
    6. Group same colors and models to increase the efficiency of the work cell (+ EDD)

    The best results were achieved with the following configurations:

| Parameter | Current | Future | Evolution |
|---|---|---|---|
| PLT (min.) | 4865.6 | 3613 | -25,7 % |
| Lateness (min.) | 331544 | 181996 | -45,1 % |
| Throughput (seats) | 1650.87 | 1662.37 | +0,7 % |

*Table 4.9: Performance evolution from current to future state (Configuration A)* ***without*** *work center efficiency improvements*

| Parameter | Current | Future | Evolution |
|---|---|---|---|
| PLT (min.) | 4865.6 | 3642,2 | -25,1 % |
| Lateness (min.) | 331544 | 137522 | -58,5 % |
| Throughput (seats) | 1650.87 | 1691,42 | +2,46 % |

*Table 4.10: Performance evolution from current to future state (Configuration B)* ***with*** *work center efficiency improvements*

- **Configuration A** (Table 4.9)
  CONWIP ← 100 articles
  ProcessMAX ← 109 min.
  Priorities ← 1 6 1 5; without efficiency improvement
- **Configuration B** (Table 4.10)
  CONWIP ← 100 articles
  ProcessMAX ← 109 min.
  Priorities ← 1 6 6 6; with efficiency improvement

An efficiency improvement can be taken into account when a same color (reduce process time by 5%) and/or a same model (reduce process time by 5%) is being processed. When a work cell produces two subsequent articles of same color and model, than the process time to produce the second one is reduced by 10%.

#### 4.2.2.4 Lean (MES) implementation

In order to achieve the future state - as simulated, a supporting Lean MES must be implemented. Figure 4.23 applies the Lean MES framework to the furniture manufacturing case. The part that was simulated by Flexsim™must be implemented as an electronic CONWIP (eCONWIP) system. That implementation can be based on the ISA 95 structure described in appendix A. The result is a Lean MES that can follow up the Lean progress by repeating the mapping exercise with aVSM. From this moment on, the functionality of the Lean MES can be maintained and expanded further by standard model changes.

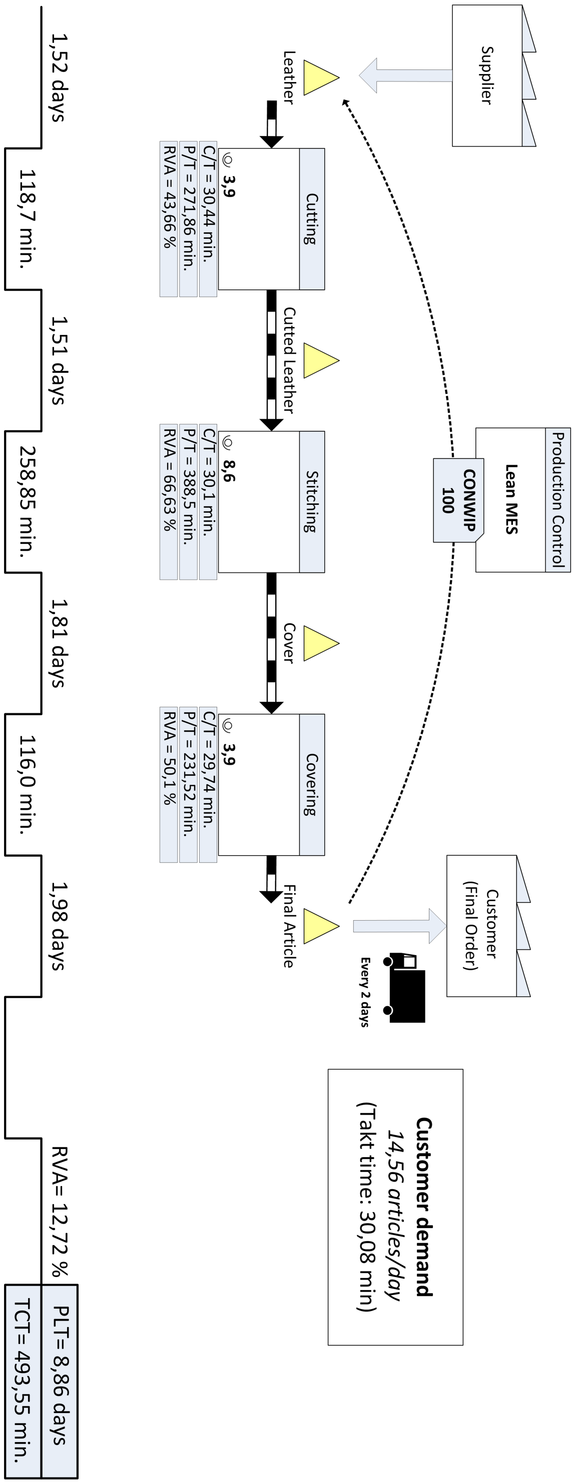



*Figure 4.22: The future state map template generated by aVSM based on the simulaion data of the configuration without efficiency improvement*

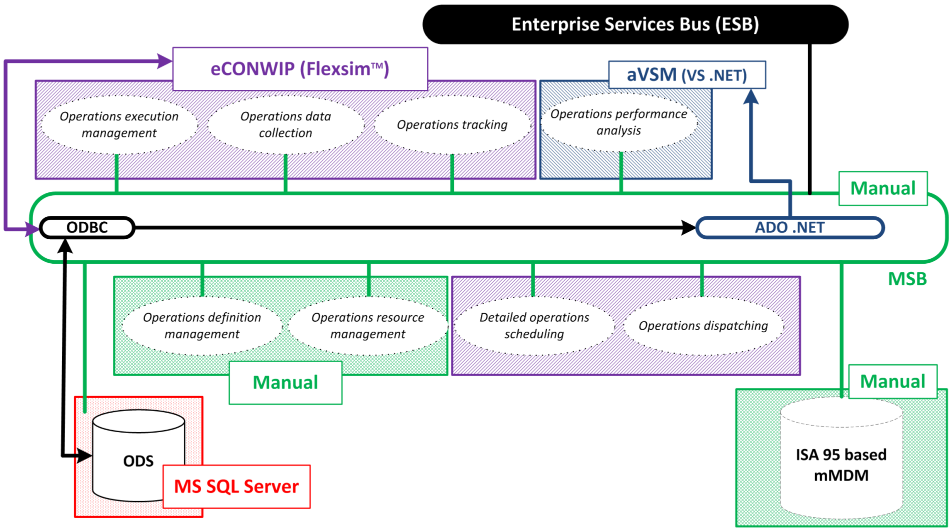



*Figure 4.23: Lean MES framework implementation for the furniture manufacturing case*

### 4.2.3 Future validation requirements

In order to fully validate the Lean MES framework, its ability to support a company to discover opportunities, guide the process, achieve the goals and maintain improvements of CI initiatives must be checked. That is only possible when the company actively cooperates within the project. Case A had a promising start as an internal Lean improvement project. But after one meeting, the project was postponed. The MES integrator could only provide the necessary operations data for an offline analysis. Case B was based on operations data that was available as a result of a MES feasibility study. An actual Lean implementation and follow up was also not possible here. There was a case C at a company producing frozen vegetables. But after a couple of meetings, the MES integrator pulled the plug due to time constraints. As no operations data was obtained, the case could not be used for validation purposes.

To enable full scale validation in the future, real Lean improvement projects must be found. A number of factors will be crucial to convince companies to allow this validation attempt in combination with their internal project:

- An operational pilot application of a Lean MES must be available. In case of a brownfield project, the only custom coding that will be left, is the mapping of the master and operations data to ISA 95 of the specific MES implementation. A greenfield project would not require any custom coding. A MES, using ISA 95 as underlying data model, is commercially available. The ODS contains all information in ISA 95 format. The possibility must be investigated to implement a pilot aVSM tool in the software. That would enable a larger scale validation of the proposed aVSM methodology in particular and the Lean MES framework in general.

- Due to the conceptual phase of the research, end users are not willing to allocate sufficient resources and in-house support for a full scale project. It would be better to search for a MES consultant, integrator or vendor who allows the project in parallel with their own implementation, update or extension of MES. Confidentiality will of course be a critical factor.

If these prerequisites are met, the validation efforts would be minimized. To validate the framework, multiple cases within various industrial sectors should be performed. The lack of real test environments obstructs the validation of MES concepts in general. Real production environments (and their control) are obviously not available for this kind of testing. New concepts are usually stress tested through simulation models in order to minimize the risk at implementation. The MES research community needs a standard dataset to evaluate MES research results. That would enable benchmarking. Datasets from a number of companies in various industrial sectors must be available. Three components must be contained in order to allow a realistic benchmark: master data (e.g. information about products, processes and personnel), operations data (e.g. performance information) and changing conditions within the production environment (e.g. machine breakdowns, operator absence, etc.). All data should be standardized to ISA 95 terminology, to create a uniform benchmarking platform. To measure the impact of specific (Lean) MES control concepts and decisions, a simulation engine could be used.

When such a benchmarking platform would be available, then commercial MES implementations could be objectively compared on a number key aspects. In the light of this dissertation, the flexibility of a MES to support and follow CI initiatives could be evaluated, resulting in some sort of Lean MES index.

## 4.3 Conclusion

The CharBox simulation case verified the different steps in the aVSM methodology. Each Lean MES activity makes use of standard ISA 95 object models to perform its task (Table 4.1). These models are stored in the ODS prototype, implemented in MS SQL Server. Typical MES support (MOM digitization) is implemented in the simulation software FlexSim$^{TM}$. The activities scheduling, dispatching, data collection, execution management and tracking are custom coded within the simulation objects. A pilot aVSM application incorporates the proposed Lean MES activities and triggers MOM optimization. The current state value stream map revealed high inventory levels and an unbalanced value stream. A pull system was introduced and configured based on the historical data of the current state map. A number of kaizen bursts were planned. Step by step, improvements are introduced into the Lean MES in order to follow the Lean changes on the shop floor and ensure the new way of working. The standard change work flows describe the necessary modifications for the different activities within the Lean MES. The Lean progress is followed up by redrawing the map.

The beverage manufacturing case shows how an existing application can be extended with Lean MES support. An ISA 95 plugin translates the necessary information to the ODS and enables the use of the standard aVSM methodology. The information requirements determine what information from the complex database must be restructured in the ODS. The selected process facts are: C/T, C/O, U/T and defects. It is a complex case, so a lot of different final products are available. By k-means clustering of the product tracking information, the different final products are grouped to three different product families. The product mix is determined by the historical data. The S-Family has the highest share and will be mapped first. The available historical data are structured on the current state map. The map shows some missing values and a number of inconsistencies. In a first improvement step, the information availability must be critically reviewed and modified by the custom reporting change work flow. A new snapshot can then be used to proceed the aVSM analysis. Without active cooperation of the company - as is the case with this offline analysis - the execution of further aVSM steps is not possible.

The furniture manufacturing case has historical data, but can start a Lean MES from scratch. The master and operations data are added to the ODS. Through current state mapping the waste is identified. First of all, a number of inappropriate measurements must be corrected: (1) Record actual start and end times of operations instead of start time and length of the operation; (2) Change the system in order to enable scanning of the sticking, stiching and singeling process; (3) Try to make a difference between setup and process times in the future situation. In the future state map a CONWIP system is introduced. Reducing the WIP will shorten PLT and create a higher manufacturing visibility and efficiency. VSM simulation suggests an initial level of 100. By systematically lowering the WIP level, problems are revealed and can be tackled. A positive effect is anticipated from the proposed realtime production control delivered by the Lean MES. The introduced eCONWIP system can be implemented using the ISA 95 structure described in appendix A.

In order to fully validate the Lean MES framework, its ability to support a company to discover opportunities, guide the process, achieve the goals and maintain improvements of CI initiatives must be checked. That is only possible when the company actively cooperates within the project. A number of factors will be crucial to convince companies to allow this validation attempt in combination with their internal project: an operational aVSM is available and the project can run in parallel with a commercial MES project. If these prerequisites are met, the validation efforts would be minimized. To validate the framework, multiple cases within various industrial sectors should be performed.

The MES research community needs a standard dataset to evaluate MES research results. Three components must be contained in order to allow a realistic benchmark: master data, operations data and changing conditions within the production environment. All data should be standardized to ISA 95 terminology, to create a uniform benchmarking platform. When such a benchmarking platform would be available, then commercial MES implementations could be objectively compared on a number key aspects. In the light of this dissertation, the flexibility of a MES to support and follow CI initiatives could be evaluated.

# 5

# Conclusions & Further Research

This doctoral research proposes the concept of a Lean MES framework. The framework structures the combination of software support and Continuous Improvement (CI) initiatives on the shop floor. This combination provides a solution for two problems that many companies are currently faced with:

1. **Lack of easy-to-use analytical workbenches for the shop floor on top of real-time data collection:** In MES, a treasure of digital information is available in support that can support waste identification and elimination. Unfortunately, most companies fail to exploit the full potential of these data.

2. **Ease of deployment and use remains a barrier to the adoption of Lean software on the shop floor**: Software systems are believed to lack the necessary flexibility to follow frequent changes and - as result - easily become obsolete. A study of AMR still shows a limited adoption of Lean IT so far.

In section 1.2, a number of research questions were defined. The conducted research provided the following answers:

1. **What is (and can be) the role of an MES in the CI cycle within MOM?**
   Chapter 2 starts with a general introduction to the two manufacturing strategies that will be combined in one framework: Lean and MES. Originally, Lean practices were considered to be based on purely manual efforts. However, Lean and IT are more and more claimed to be interdependent and complementary. A distinction is made between a Lean look at IT and software support for Lean practices. Some research has been reported on the combination between Lean and ERP. Due to ERP's inability to efficiently manage shop floor processes, MES emerged. The

main goal of MES is automating activities and information flows in the MOM layer. However, the implementation of MES can reveal opportunities to further improve manufacturing operations. Benefits can reach further than the initial goal. Literature discussing the combination of MES and CI is scarce. Section 2.4 gives an overview of the role of MES in CI. If an MES is (or will be) implemented, it can facilitate future CI initiatives; such as Lean. MES is believed to be an enabler of CI programs. In order to avoid the most common pitfalls, an efficient implementation and integration of the MOM layer is crucial. The DMAIC methodology was used to illustrate the role of MES in process improvement. The everlasting change lays a dual task on MES: supporting the change process and controlling the achieved improvements.

2. **What is the concept of a Lean MES framework?**
Considering the combination of Lean tools and techniques (MOM optimization) and MES production control (MOM digitization), a company approach can be gradually classified into three categories: (1) No alignment; (2) Lean MES alignment; and (3) Lean MES integration. When the alignment is automatically maintained on a regular basis, then a Lean MES integration is achieved. The ISA 95 standard is introduced as common information model to achieve the proposed Lean MES integration. Standard analytical tools must base their analysis on ISA 95 object models. As a consequence, these tools can provide data and analysis support to all systems that speak ISA 95. Typical Lean operational changes are defined as standard ISA 95 change work flows. That enables an automatic reconfiguration of MES to follow the changes. The framework is illustrated by the manufacturing 2.0 SOA architecture. Each MOM activity comprises functions and tasks, each of which consumes manufacturing master data to execute real-time production and support operations work flows. The extra information about the Lean data and functionality mapping and standard Lean model transitions are added to mMDM, enabling the different activity models (with incorporated Lean support) to cooperate as a Lean MES. The different components of the Lean MES framework are listed in section 3.2. The framework can be used to expand an existing Lean MES or to configure one from scratch.

3. **How can MES be restructured to support standard decision making?**
The ISA 95 models originally focus on push production principles. In this work, the application of the object models to typical Lean functionality is illustrated. Automated Value Stream Mapping (aVSM) is matched with ISA 95 as an example. The lack of attention of MES towards flow efficiency justifies the choice of detailed description of VSM. In future research, the same exercise can be done for other standard CI tools and techniques. The requirements for future expansion of the framework are applied to TPM. Section 3.3 shows how the phases of the aVSM methodology can be supported by standard tools. Based on available ISA 95 operations data, product families can be identified and a initial product family can be

selected. A current state map can be generated and documented by standard facts. Extra tools (e.g. product mix, process time variability, takt time calculation, line balancing, IN/OUT diagram for WIP, kanban loop configuration, etc.) can support the manual analysis in order to construct a future state map.

4. **What is a feasible change management approach for MES to follow typical Lean changes?**
   In section 3.4, an ISA 95 based change management approach is introduced. The definition of standard change work flows for typical Lean operational changes, reduce the change-over time and possible errors within MES. The support for a number of operational changes, that relate to aVSM, are discussed. A method to populate the ISA 95 ODS with historical operations data of a legacy system, is described. Through the standard change work flows *new production introduction* and *custom reporting*, all available information that can be useful for the aVSM methodology is configured. When the future state is known, a guided transition from push to pull production control, can automatically migrate the MES data model to its new state while preserving its integrity. By providing change work flow definitions for typical Lean operational changes, MES can be easily reconfigured as a result of CI initiatives. Where MES change management is currently considered case by case, ISA 95 based change management describes a general approach for typical Lean operational changes. Each system can be mapped to the ISA 95 models in order to determine the required change management steps. A change management approach in function of time matches the dynamic character of MES to the static nature of Lean. First a snapshot of MES is taken to perform an offline analysis. Each improvement activity of the Lean implementation plan is first implemented on the shop floor (change management of people, processes and technology). The last step in the implementation is a synchronization of MES with the offline future state ODS. As information requirements are modified during the Lean implementation steps, a new snapshot must be taken to follow up the Lean progress. Supporting the VSM methodology by MES decreases the lead time of the offline analysis. That means that the improvement can be applied to the shop floor much sooner. The recorded change work flows - during the offline analysis - can be immediately applied to MES after the shop floor implementations are finished. Both aspects can significantly speed up the improvement cycle.

The main contribution of the Lean MES framework is a first attempt to formalize the integration of two proven approaches on the shop floor in order to boost their efficiency and effectiveness. However, the impact of the framework can be stated from various points of view.

1. **Research community:** The literature review (chapter 2) indicated some under researched topics in the fields of MES and Lean. Creating and maintaining shop floor visibility is seen as the main goal of an MES. But what the requirements are in order to achieve that visibility and how it can be maintained in a dynamic produc-

tion environment, still remains an open issue. On the other hand, the value of Lean IT support has been acknowledged in recent literature. But there are still practical boundaries to the actual use of these systems on the shop floor. The Lean MES framework defines the integration of both proven approaches in order to complement each other. Lean can be used to achieve and maintain MES visibility, while MES boosts the practical performance of Lean. The integration is achieved by mapping the two standards within the MOM framework.

2. **Standardization organizations:** ISA publications in this domain (i.e. ISA 95) focus on push environments. All terminology reflects to the PPC domain. But none of the ISA 95 publications contains a link to Lean (control) principles. In addition, the MOM domain is more than only a PPC integration project. It contains all functionality to support production, quality, inventory and maintenance activities. As CI initiatives are highly interconnected with those activities, future ISA 95 publications should pay more attention to them. The modeling of Lean principles and tools is possible with the ISA 95 object models that are currently available. The proposed ISA 95 match with Lean concepts (appendix A) can be used as starting point to generalize the definitions away from the push focus.

3. **MES consultants and integrators:** As CI initiatives are crucial to strive to operational excellence and maintain production visibility, they should be incorporated in the selection (implementation) process for MES. The Lean MES framework serves that purpose. The alignment between CI and MES can be formalized and will be taken into account from the beginning of the project. In addition, featured (Lean) improvements could help to justify the MES investments. It is not trivial to put featured MES benefits against the high installation costs and possible risks.

4. **MES software vendors:** The Lean MES framework defines a standard approach to combine production visibility with process improvements. In practice, a number of standard configurations - e.g. for the different manufacturing sectors: food, pharma, metal, industrial machinery, etc. - could be set up as typical starting point. From there on, further configuration can be initiated in order to fit the specific requirements of the customer. For example, the requirements for custom reporting can be specified in order to collect the right information at the right time at right place in production. Or production control principles can be set up to connect all processes in order to achieve an optimal product flow. Based on the Lean MES framework, the commercially available software packages could be tested on Lean MES conformity.

5. **MES end users and Lean practitioners:** A Lean MES will fix the shortcomings of both approaches separately. MES will be more user friendly, up to date, flexible, etc. because of Lean information management. The MES visibility can drive the Lean journey, validate future states, suggest CI initiatives, implement more complex control issues for Lean, impose the improved way of working and follow up Lean progress.

Within the proposed Lean MES framework, aVSM is the first step toward a standard analytical workbench on top of real-time data collection. By expanding the CI support, a standard collection of tools can be developed to enable full scale MOM support. A short description was given for the integration of TPM. Other options are TQM, Six Sigma, Lean selection and planning intelligence, etc. Each system that speaks and understands ISA 95 could be plugged in to use the predetermined set of tools to optimize MOM.

There is a lack of real test environments for MES concepts. That makes it very difficult to validate them. As first step, the feasibility of the Lean MES framework is checked. The CharBox simulation example in section 4.1 verifies the ability to incorporate Lean functionality and changes within ISA 95. Through manual (re)configuration of the MOM database model and functionality, the Lean MES can be initiated and maintained. In a second step, the potential of the standard tool to automatically extract useful information is verified. The selected cases each illustrate a different setting for the application of the framework. In the two case studies; of different size, industry and complexity; available historical data are standardized to the ISA 95 format and analyzed by the proposed aVSM methodology. Case A features a big beverage manufacturing company and illustrates the identification of product families based on historical operations data. The 131 final products are grouped by three product families. The S-Family is selected for the first mapping exercise. Case B analyses the situation of a small furniture manufacturing company. Based on the available operations data, a current state map is drawn. The map identifies that processes maintain a high WIP. The introduction of a constant WIP system is suggested to limit the amount of WIP. The results of both cases illustrate that aVSM extracts valuable information from the available historical data. By transforming the data to standard ISA 95 models, the same tool can be used to support the analysis of both cases. The standard change work flows protect the integrity of the Lean MES. Section 4.2 acknowledges the fact that the Lean MES integration creates new insights and that the standard change work flows facilitate possible model transitions for both cases. However, the two cases are insufficient to really validate the approach. Based on the lessons learned from the experience of both cases, the future validation requirements are set.

In order to fully validate the Lean MES framework, its ability to support a company to discover opportunities, guide the process, achieve the goals and maintain improvements of CI initiatives must be checked. That is only possible when the company actively cooperates within the project. Unfortunately, no such cases were available during the doctoral research. To enable full scale validation in the future, real Lean improvement projects must be found. Multiple projects within various industrial sectors should be performed. An MES, using ISA 95 as underlying data model, is commercially available. The ODS contains all information in ISA 95 format. The possibility must be investigated to implement a pilot aVSM tool in the software. That would enable a larger scale validation of the proposed aVSM methodology in particular and the Lean MES framework in general.

The lack of real test environments obstructs the validation of MES concepts in general. The MES research community needs a standard dataset to evaluate MES research results. All data should be standardized to ISA 95 terminology, to create a uniform benchmarking platform. To measure the impact of specific (Lean) MES control concepts and decisions, a simulation engine could be used. When such a benchmarking platform would be available, then commercial MES implementations could be objectively compared on a number key aspects. In the light of this dissertation, the flexibility of a MES to support and follow CI initiatives could be evaluated, resulting in a Lean MES index.

Awaiting the publication of part 4 of ISA 95 (which will describe the information exchange within the MOM layer), the object models of part 1 & 2 are currently used to model the integration. Without a doubt, part 4 will contain more specific models for the information exchange between the different activities. For example, a *KPI definition* model could facilitate the definition of typical VSM facts and their calculation methods. When part 4 is published, the Lean data and functionality mapping should be reviewed. It will also be interesting to see to what extent Lean (or CI) terminology will be incorporated in the document.

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# A

# Matching Lean and ISA 95 terminology

*The integration of Lean functionality in the MES framework can be achieved by using ISA 95 terminology. A general overview is given of the match between Lean and ISA 95. In particular, the ISA 95 representation of the aVSM methodology (A.1), VSM icons (A.2); typical VSM facts and calculations (A.3); and pull production control principles (A.4) are described.*

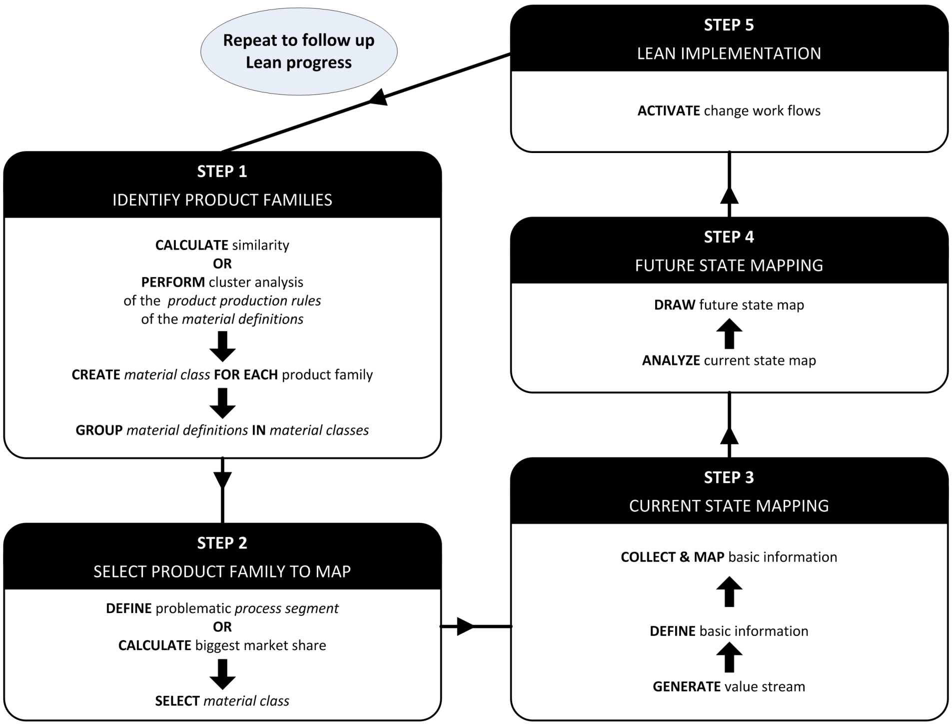



*Figure A.1: The standard phases of the aVSM analysis*

## A.1 Representation of the aVSM methodology

Based on the standard phases of the VSM analysis, the necessary content and integration of the ISA 95 activity *performance analysis* (or more detailed, the subactivity aVSM) is discussed: identify product families, select initial exercise, map the current state, map the future state, manage the changes and follow up the Lean progress. Figure A.1 summarizes the different phases applied to aVSM. The following sections will discuss how each step is supported by the proposed Lean MES.

### A.1.1 Identify product families

In a first step, the product family that will be mapped must be identified. Similarities between product work flows are searched to define product families. A standard approach is the construction of a product matrix. The different tasks on the factory floor are listed as column headers, the company's final products make the row headers. For each final product an 'X' marks the tasks necessary to manufacture it. Products that possess high commonality of tasks should be grouped within a single product family and value stream mapped as a single map. As a general rule, a similarity of 70% or higher is used as

| Process Segments / Product Production Rules | PS1 | PS2 | PS3 | PS4 |
|---|---|---|---|---|
| PPR1 | *Product Segment?* | *Product Segment?* | *Product Segment?* | *Product Segment?* |
| PPR2 | *Product Segment?* | *Product Segment?* | *Product Segment?* | *Product Segment?* |
| PPR3 | *Product Segment?* | *Product Segment?* | *Product Segment?* | *Product Segment?* |
| PPR4 | *Product Segment?* | *Product Segment?* | *Product Segment?* | *Product Segment?* |
| PPR5 | *Product Segment?* | *Product Segment?* | *Product Segment?* | *Product Segment?* |
| PPR6 | *Product Segment?* | *Product Segment?* | *Product Segment?* | *Product Segment?* |

*Table A.1: The product matrix structure to determine product families based on ISA 95 terminology*

grouping boundary. As an alternative to using a matrix to identify all the value streams in your organization, it is possible to use the 30 seconds exercise to identify the basic content of a value stream to be mapped.

The identification and selection of product families are mostly performed purely manual. By integrating Lean into MES, software support can assist this first step in the analysis. The activity *definition management* contains all (theoretical) information about product routings. When available, the activity *tracking* can provide actual product routings to enable an even more realistic analysis. By analyzing the commonality of these product flows, a suitable technique can be proposed to map the value stream. A deviation from traditional VSM can be suggested for complexer cases. However, as traditional VSM is the foundation, its integration with MES will be tackled in this initial description. To integrate VSM functionality within MES, a match must be made between VSM and ISA 95 terminology. The *product production rules* (Figure A.2) are defined as the information used to instruct a manufacturing operation how to produce a product[1]. This may be called a general, site or master recipe, SOP, product routing or assembly steps based on the production strategy used. These object models within MES can be used to analyze the commonalities between different product routings to identify product families. The product production rule consists of a sequence of product segments. Each *product segment* defines the information about one step in the production of a specific final product. A *process segment* describes the product-independent tasks within production. So, a process segment can be related to multiple product segments. Or otherwise, multiple product segments can be executed by one process segment. In the product matrix (Table A.1), process segments are the tasks and must be listed as column headers. The final products in the row headers are the different product production rules. A cell can be marked with an 'X' if the product production rule (row) contains a product segment that corresponds to the process segment (column). Based on this information a simple similarity percentage can be calculated or more complex clustering algorithms can be used to create optimal product family groupings.

After analysis, all final products must be grouped in relation to their product fami-

[1]Typically used for the purpose of planning and scheduling.

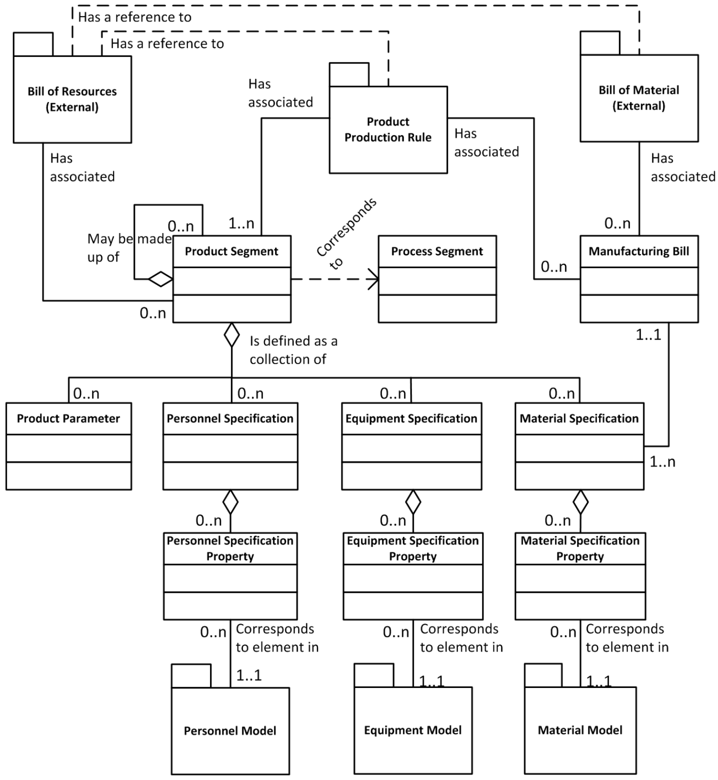



*Figure A.2: The product production rule information within the product definition model can be used to analyze the commonalities between different product routings to identify product families. (Source: ISA 95 (2000))*

lies. Figure A.3 lists the ISA 95 terminology for the material classification. Each product family must be represented by a separate *material class* and contains the different final products as *material definitions*. This classification of final products supports the process of current state mapping. Based on the selected material class (or product family), the information of the concerned *material (sub)lots* (actual products) can be collected in support of the analysis. After this initial classification, product families can be critically reviewed on a regular basis or after new product introductions. The *product definition* data must validate the current product family classification. If available, data of the activity *tracking* can validate the current structure of the product definition.

## A.1.2 Select initial exercise

The selection of the first product family to map and analyze may be straightforward in most cases. Typically a product family with promising ROI opportunities will be tackled first. Product families could be automatically prioritized based on available historical

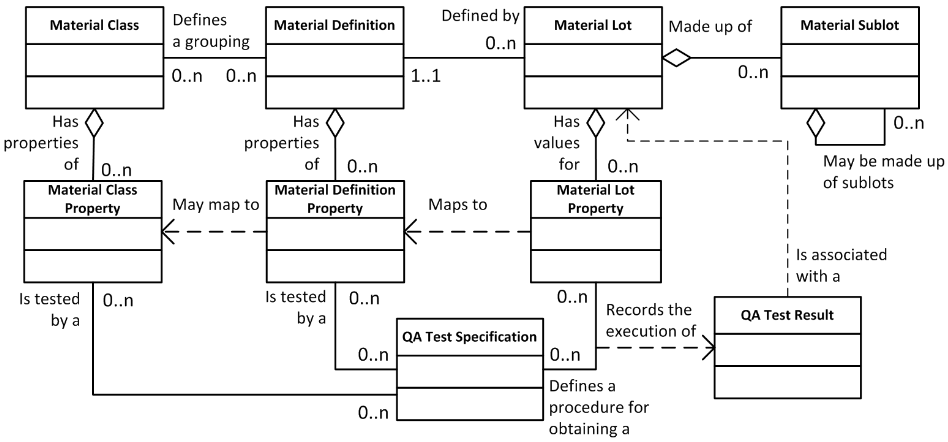



*Figure A.3: The material model of ISA 95 provides a standard terminology for material classification (Source: ISA 95 (2000))*

information. For example, problematic processes could require the first focus. If the problematic *process segment* is known, then all corresponding *product segments* link to a selection of *product production rules*. The corresponding *material definitions* are contained by one or more material classes. One of these classes would be a good product family to start from. Focusing on product families that consist of high quantity or high revenue products is advisable to enable quick wins. The *production performance* model incorporates the actual produced quantities of final products. Summing these values over a certain period of time gives an idea of the product mix. The material class with the biggest share is an appropriate candidate for the initial exercise. Figure A.4 shows a pie chart example of the product family shares of the actual produced quantities. The material class *product family A* would be selected for the initial exercise.

### A.1.3 Current state mapping

To map the current state using VSM, you must walk the process. However, as stated in section 2.4, the available historical data in MES can be used to support the manual exercise[2]. A number of configuration steps are necessary to determine what will be mapped and to integrate the generation of the current state map within ISA 95. The VSM tool itself allows for flexibility to work within any setting, but still boundaries exist. The rules that do exist focus on three elements (Nash and Poling, 2008) and will be used to explain the integration requirements:

- *Standardization of icon use, as much as possible*

[2]Using the eVSM template as starting document can expose problems or wrong data in MES. Another option is to validate the manual exercise by the generated eVSM template. Contradictions must be investigated to expose and correct manual or MES errors.

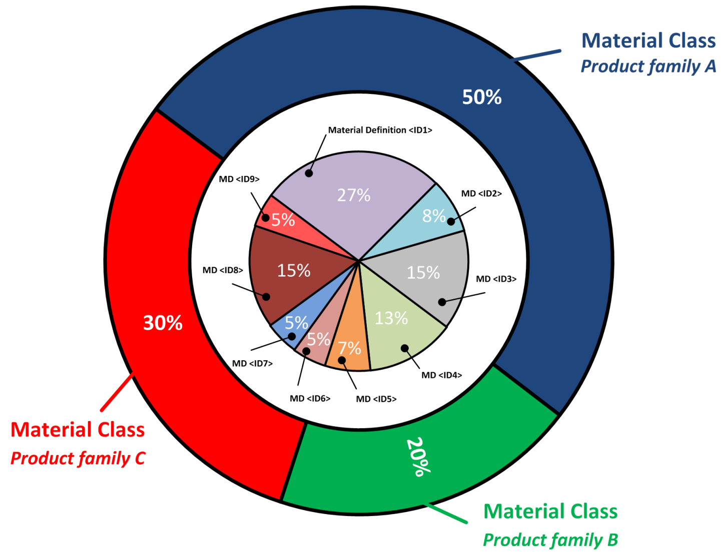



*Figure A.4: A pie chart example denoting the product mix related to the ISA 95 terminology of material definitions and classes.*

The basic icons used in VSM are a combination of flowcharting icons and unique shapes used to visually represent the various tasks and functions within a map. Icons are categorized into several groups:

- Process, entities, inventory and associated data
- Flow, communication, signals and labels
- People and transportation

It is common practice to create your own icons - but only when necessary. The most important part of creating your own icons is to thoroughly explain the icon to the audience and consistently use this icon from the point of creation forward. An eVSM tool can support the mapping exercise and impose standard work by providing a list of standard VSM icons. To provide aVSM, these icons must be matched to ISA 95 terminology. Tables A.2, A.3 and A.4 give an overview of the ISA 95 representation of the standard components of a value stream map. The tasks or activities linked within the value stream (as well material as information flow) are represented by *process segment* objects. Based on the standard icon definitions, a process mapping can be incorporated in MES. The availability of operations data for each object will provide useful information for future Lean efforts. Section A.2 provides a more detailed description of the ISA 95 translation of the standard VSM icons.

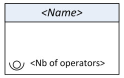
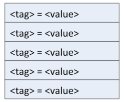
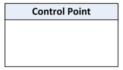
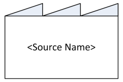
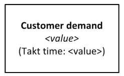
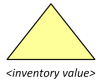
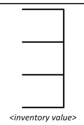
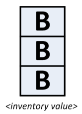
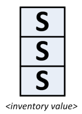
| Icon | Icon name | Description | ISA 95 object | Use of standard attributes (*) and additional properties |
|---|---|---|---|---|
|   | **Process box** | The process box identifies a task within the value stream. The box shows where flow starts and stops | **Process Segment** | *ID** ← <Name> of the task<br>*Type* ← 'Production Process'<br>*Operators* ← <Nb of operators><br>*Task List* ← Production Schedule |
|   | **Data box** | Lists a number of facts that describe the operation. | **Process Segment Parameter** | Add *Name** and *Value** for each required fact on the map, e.g. C/T, C/O, U/T. |
|   | **Control point** | Description of the single point that controls the flow and function of the value stream | **Process Segment Parameter** (Umbrella) | *Name** ← Control Point<br>*Value** ← e.g. MES |
|   | **External source** | Defines the supplier(s) and the customer(s) of the value stream | **Process Segment** | *ID** ← Customer01<br>*Type* ← External Source |
|   | **Customer demand box** | Lists the customer demand information | **Process Segment Parameter** (Customer Source) | *Name** ← e.g. Customer demand<br>*Value** ← e.g. 117<br>*Unit of Measure** ← e.g. boxes/day |
|   | **Inventory** | Defines the number of parts in between processes in the value stream | **Process Segment** | *Type* ← 'Push Inventory'<br>*Duration** ← <inventory value> |
|   | **Work queue** | Similar to inventory, but for a transactional value stream | **Process Segment** | *Type* ← 'Work Queue'<br>*Duration** ← <inventory value> |
|   | **Supermarket** | Inventory location within a pull control system | **Process Segment** | *Type* ← 'Supermarket'<br>*Duration** ← <inventory value>, number of days of inventory to maintain<br>*Kanban List* ← Production Schedule |
|   | **Buffer stock** | A buffer stock is maintained to be able to react to a sudden increase of customer demand | **Process Segment** | *Type* ← 'Buffer Stock'<br>*Duration** ← <inventory value>, number of days of inventory to maintain |
|   | **Safety stock** | A safety stock is maintained to be able to react to possible internal errors | **Process Segment** | *Type* ← 'Safety Stock'<br>*Duration** ← <inventory value>, number of days of inventory to maintain |

*Table A.2: Overview of how process, entities, inventory and associated data icons of VSM are matched to ISA 95 terminology*

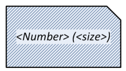
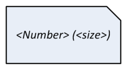
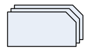
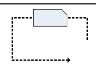
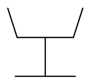
| Icon | Icon name | Description | ISA 95 object model | Use of standard attributes (*) and Additional properties |
|---|---|---|---|---|
|  | **Push arrow** | Flow of materials being pushed downstream | See inventory | |
|  | **Pull arrow** | Flow of materials (kanban) being pulled downstream by pull signals (e.g. kanban) | See supermarket | |
|  | **Physical pull** | Flow of materials physically being pulled downstream | See supermarket | |
|   | **FIFO lane** | FIFO lane limits the amount of WIP and ensures work sequence | **Process Segment** | *Type* ← 'FIFO'<br>*Duration** ← <max value> |
|   | **Heijunka (Load leveling) box** | Tool to help level both the mix and volume of production | **Process Segment** | *Type* ← 'Heijunka'<br>*Duration** ← <pitch><br>*Priority rule* ← e.g. production mix matrix<br>*Pacemaker* ← links to the pacemaker process segment |
|   | **Withdrawal kanban** | Trigger for pulling material from a supermarket to a downstream process | **Segment Requirement** | *ID** ← Card ID<br>*Material Definition (or Class)** ← material description<br>*Segment** ← link to supplier process segment<br>*Material Produced Requirement* - Quantity** ← container size<br>*Material Produced Requirement* - Location** ← link to the customer process segment |
|   | **Production kanban** | Trigger for pulling material from a process to a downstream supermarket or process | **Segment Requirement** | *ID** ← Card ID<br>*Material Definition (or Class)** ← material description<br>*Segment** ← link to supplier process segment<br>*Material Produced Requirement* - Quantity** ← container size<br>*Material Produced Requirement* - Location** ← link to the customer process segment |
|  | **Kanban batch** | A batch of Kanban cards | **Production Request** | *Segment Requirements** ← links to the different kanban cards |
|  | **Kanban path** | Determines the path a kanban card must travel from supplier to customer | See kanban (segment requirements attributes: customer → supplier → customer) | |
|  | **Kanban post** | A location where kanbans are collected | **Production Schedule** | *Segment Requirements** ← links to the different kanban cards<br>*Segment** ← process segment where kanbans are queued<br>*Production Requests** ← Grouping of different kanban card types, e.g. different material definitions at kanban wall |

*Table A.3: Overview of how flow, communication and signal icons of VSM are matched to ISA 95 terminology (part 1)*

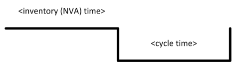
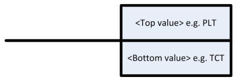
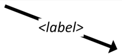
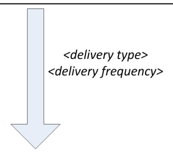
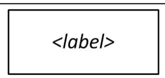
| Icon | Icon name | Description | ISA 95 object model | Use of standard attributes (*) and Additional properties |
|---|---|---|---|---|
|   | **Kaizen burst** | The definition of improvement ideas | **Process Segment Parameter** (of the affected process segment) | *Name** ← Kaizen burst ID<br>*Value** ← improvement idea |
|   | **Timeline segment** | A segment of the timeline documenting one process step | No separate objects, but calculated based on the longest path in the value stream | |
|   | **Timeline total** | A segment of the timeline containing overall values | No separate object, but calculated based on the longest path in the value stream | |
|   | **Manual Communication** | Adds manual communication flow on the map. | **Process Segment** | *ID** ← ID of the task<br>*Description** information <label><br>*Type* ← 'Manual Communication' |
|   | **Electronic Communication** | Adds electronic communication flow on the map | **Process Segment** | *ID** ← ID of the task<br>*Description** ← information <label><br>*Type* ← 'Electronic Communication' |
|   | **Customer / Supplier Delivery** | Adds delivery information on the map, from supplier and to customer | **Process Segment** | *ID** ← e.g. customer delivery<br>*Type* ← 'Delivery'<br>*By* ← Delivery type, e.g. truck<br>*Frequency* ← e.g. 1x /day |
|   | **Label** | Adds a label icon within the information flow | **Process Segment** | *ID** ← ID of the label<br>*Type* ← 'Label'<br>*Description** ← <label> information |

*Table A.4: Overview of how flow, communication and signal icons of VSM are matched to ISA 95 terminology (part 2)*

- *The basic layout of the map*
All maps are alike. Communication appears on top. Process or product flow appears in the middle and always flows from left to right. Timelines and travel distances are shown on the bottom. Process boxes, push and pull arrows, inventory locations and communication lines are always used in a similar fashion. This standard layout enables the development of a support tool for one or more of the stated compartments of the current state map. The support MES can give, depends on its implementation level and on the information that is available.

- *Creation of a structured method of documentation and presentation to make the results clearer to the audience*
The drawing steps for the aVSM case must follow the same structured method as the manual exercise. aVSM - as part of MES - imposes the standard analyzing steps, sends requests for (available and/or future) information to other activities and generates a template that can be completed further by walking the process. This work flow for drawing the current state map consists of three steps:

    1. **Select the product family and generate the value stream**
    A list of product families was created previously and all material classes (containing final products) are now enlisted as options. After selection, some general information about the selected product family can be drawn on the top of the map (e.g. product family name, final products contained, etc.). If the activity *tracking* is implemented in MES, the actual value stream can be generated automatically. In ISA 95, each production task performed by a *process segment* generates a *segment response*. Figure A.5 shows how this object model represents the production information regarding the actual use of resources; such as material, personnel and equipment; of the performed task. A suitable time frame must be entered to limit the scope of the data analysis.

       Algorithm 5 shows the basic steps in order to generate the value stream of the current state map for a given product family. As in the manual case, the map is drawn in opposite direction of the value stream itself. The last step of the value stream is the process segment of which the corresponding segment responses have a final product(s) (material definition) of the product family (material class) as *Material Produced Actual*. Then, for each *Material Consumed Actual* of the segment responses, the next process segment(s) (with that material type as *Material Produced Actual*) is (are) drawn in front of the previous one. These steps must be repeated until the beginning of the value stream, the receiving of the raw materials. In algorithm 5, the recursive calling of procedure *CONNECT* makes sure that all paths within the value stream are drawn. The material definitions are the glue to connect the different process segments of the material flow. The process segments are drawn with the VSM icon *process box*. In between all process segments, empty space is provided to add transport, inventory and communication icons in a later stadium. Figure

```
procedure GENERATEVALUESTREAM(material class)
    for all material definitions in material class do
        Connect(material definition)
    end for
end procedure

procedure CONNECT(material definition)
    SR ← segment responses where material produced actual = material definition
    for all process segments corresponding to SR do
        Draw process segment information on map according to the segment type
        for all materials consumed actual in corresponding segment response do
            Connect(material consumed actual)
        end for
    end for
end procedure
```

*algorithm 5: Generate the value stream of the current state map for a given product family*

A.6 shows the conversion of ISA 95 objects to basic components of the value stream.

In a next step, the flow signals between the process segments must be documented. As inventory (and transport) activities also can be considered as operations, each one is represented by an additional process segment (see icons in tables A.2, A.3 and A.4). An extra property *segment type* differentiates between a production process, a push inventory activity, a FIFO system, a kanban controlled supermarket, a delivery, etc. Each type defines extra properties to incorporate its specific attributes. This info can also be used to draw part of the information flow on the map, considering the production control of the different processes (e.g. kanban signals). The segment type determines how the info will be mapped. Again, all activities of the process segment must result in segment response objects. They will be necessary to calculate the information required by the map; such as inventory time values. The time values of the 'non-production' segment responses always connect the segment responses of the production processes. This ensures that all materials are linked to a particular process segment during the whole value stream, enabling the mapping of that value stream. The non-value-adding inventory times can be averaged over all segment responses (by comparing both enter and leave times of the same material (sub)lot). Another way is to calculate the time value of the current inventory level. Figure A.7 shows how the flow types can be mapped using the additional process segments. In each process segment, the material consumed and material produced requirements refer to the same material definitions. The black boxes indicate the information requirements of the map.

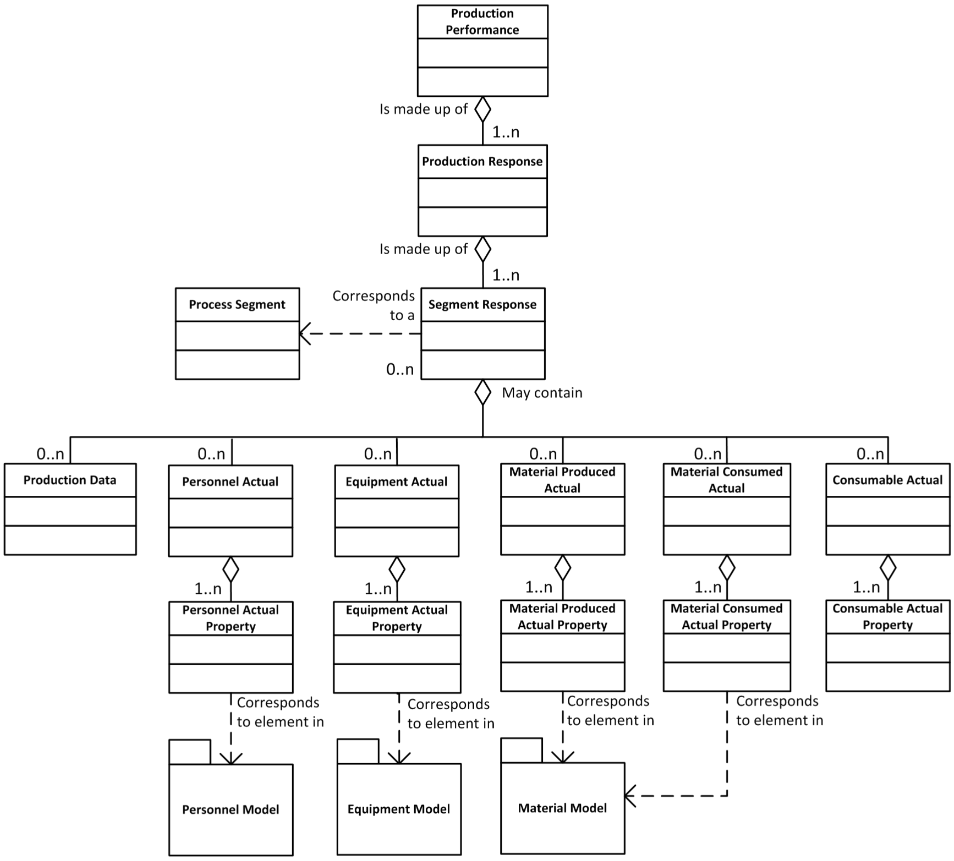



*Figure A.5: The production performance model of ISA 95 provides a standard structure to represent and communicate actual production information (Source: ISA 95 (2000))*

If no tracking data is available, then the activity *definition management* can provide the theoretical value stream documented by the *product production rules*. Instead of the segment response objects, now the product segment objects of the product production rule determine the value stream of corresponding process segments.

2. **Define basic information about the current state**
In a next step, basic information is added to the map. The *resource definitions* of the different process segments are requested from the activity *resource management*. These models contain the available information within MES. Below each process box on the map, a *data box* icon is drawn. The provided information is listed and, when extra information is necessary, extra properties (or parameters) can be configured to list additional values for each process segment. The (standard) formulas for the calculation of typical VSM

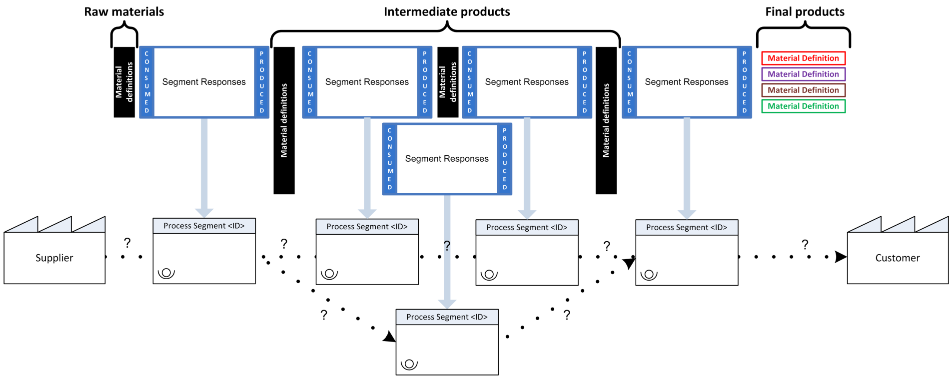



*Figure A.6: The generation of the basic components of the value stream based on ISA 95 objects*

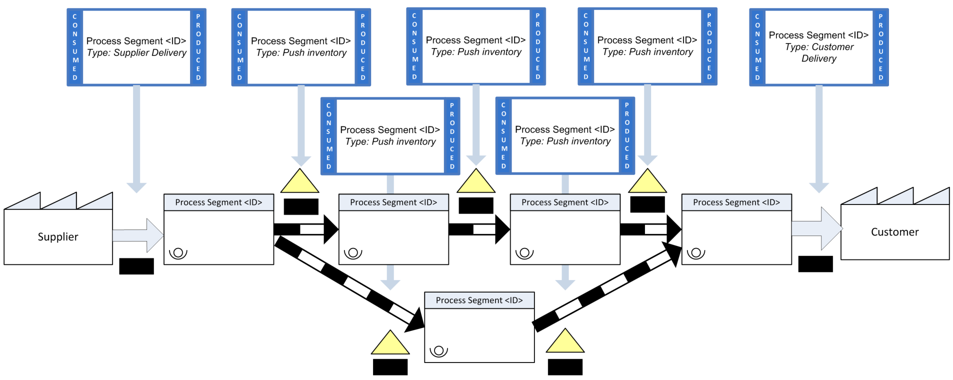



*Figure A.7: The generation of the flow in between the processes of the value stream based on ISA 95 objects*

facts and other (custom) KPIs can be configured using the activity *definition management* by form of standard ISA 95 models and calculations. Some examples are listed in table A.5. For example, the cycle time is the average time between the production of two subsequent good products. This value can be calculated for each process segment by dividing the total production time by the total number of good products produced by the process segment within the time frame of the data analysis (equation A.1). How these calculations can be defined in form of standard ISA 95 models in the ODS is currently not defined. However, part 4 of ISA 95 will cover internal MOM transactions and - when published - could come up with a solution. For the pilot application of aVSM, the calculations are hard coded. A possible alternative could be the use of Structured Query Language (SQL) queries in combination with simple mathematical functions. Equation A.2 illustrates the C/T calculation by using SQL queries. Section A.3 provides a more detailed description of the ISA 95 translation of a number of standard VSM facts and their calculation method. Most of the calculations are based on information from segment response objects. In order to inform the *tracking* activity of the required structure and values of these segment response objects, a *requested segment response* is provided.

| Symbol | Fact or KPI | Description |
|---|---|---|
| C/T | Cycle time | The average time between the production of two subsequent good products. |
| C/O | Change-over time | The average time between production runs, required to set up a machine/process |
| U/T | Uptime | The percentage of time that a piece of equipment works properly when the operator uses it for the prescribed task. |
|  | Operator count | The number of operators that work in the process segment. |
| W/C | Work content | The total amount of actual value-added and non-value-added labor time associated with a process. |
| defects | Defect rate | Defines the ratio of defects to the total number of products produced. |
| Avail. | Availability | The percentage of time that a piece of equipment - shared between two or more value streams - is available for production of products in the value stream being mapped. |
| OEE | Overall Equipment Effectiveness | A hierarchy of metrics which evaluates and indicates how effectively a manufacturing operation is utilized. |
| P/U | Parts used | Number of components or parts used at the process step. |
| P/T | Process time | The average production time for a product by the process. |

*Table A.5: A number of typical VSM facts that can be calculated based on standard ISA 95 models*

$$C/T = \frac{\sum_{i=0}^{n-1} (E_i - S_i)}{\sum_{i=0}^{n-1} \sum_{j=0}^{m-1} Q_{i,j}} \tag{A.1}$$

with

$n$ = Number of segment responses of activity type *production run*

$E_i$ = Actual end time of segment response $i$

$S_i$ = Actual start time of segment response $i$

$m$ = Number of material produced actual objects of segment response $i$

$Q_{i,j}$ = Quantity of material produced $j$ of segment response $i$

$$C/T = \frac{A}{B} \tag{A.2}$$

with

$A$ = SELECT SUM(DATEDIFF(MINUTE, [Actual End Time], [Actual Start Time]))
FROM [Segment Response]
WHERE Type = 'production run'

$B$ = SELECT SUM(Quantity)
FROM [Material Produced Actual] p, [Segment Response] s
WHERE p.[Segment Response] = s.ID AND s.Type = 'production run'

As an organization gains the experience of mapping its own value streams, other significant items of information specific to their environment will become visible. It is important to not overlook these opportunities. They may become and integral piece of basic information that the VSM will need to collect and map in the future. In section 3.4 a change management approach is proposed to deal with these changing information requirements.

Of course, not all facts have a possible match within MES, some can only be collected manually. In those cases, an open space can already be reserved in the data box, indicating the data requirements for the manual data collection. Some examples:

- Non-value-added time ($NVA$): The amount of time (part of C/T) where no value is added to the product.

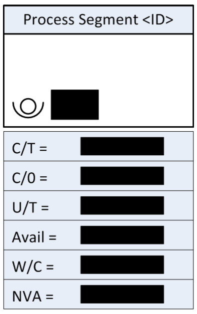



*Figure A.8: A possible result of a data box after the definition of the basic process information*

- 5S scores from 5S system audits
- Safety risk assessment scores
- Number of pieces of paper found in the process step
- Travel distance of products or operators

Figure A.8 gives a possible result of a data box of one of the processes of the value stream after the definition of the basic process information. The black areas symbolize the required information to fully document the map.

Collecting the communication flow of the value stream is predetermined to be manual, since most of the communication is actually performed in a manual, paper-based way. Figure A.9 shows the typical components of the communication flow on a value stream map in case of a push production environment:

1. *Control point:* Within every value stream there is a single point that controls the flow and function of the value stream. This single point determines what is produced when, in what quantity; and at what pace. For most manufacturing operations, this is the production control department or production manager, depending on the size or structure of the company. The control point is drawn in the middle of the page at the top in between the customer and the supplier. If a computer application is part of the control system, then its name can be documented in the box (e.g. MRP II, ERP or MES). Production control is further documented from the control point to the processes of the value stream by manual and electronic communication (see point 6).
2. *Customer orders:* This communication describes how and when customer orders arrive at the control point (e.g. by phone, by fax, by mail, etc).
3. *Purchase orders:* An indication of how and when raw materials are being ordered from the suppliers.
4. *Supplier deliveries:* This link between supplier and production states the way and the frequency of supplier deliveries.

5. *Customer deliveries:* This information determines the way and the frequency of the transports to customers.
6. *Production control:* Starting from the control point, every step of communication toward the production floor is mapped. The two extremes in the case of push production control are:
   a. *Fully automated by MES:* If production control is completely supported by MES, then communication is done by electronic signals from the control point all the way down to the work cells. Figure A.9 shows the ISA 95 terminology for the activities concerning push production control. The *production schedule* model lists all production orders as *production requests* (Figure A.10). Each production request corresponds to a *product production rule* documenting the steps to produce a final product. A production request consists of a series of *segment requirements*. Each of them lists the resource requirements to perform a production step and corresponds to a *process segment*. The activity *detailed scheduling* is responsible for updating and refining this timetable taking into account the progress of production. *Dispatching* pushes all operations, defined as segment requirements by the detailed production schedule, toward the processes for a specific time frame (e.g. one shift). The segment requirements are sorted in a dispatch list and queued by the activity *execution management* for each work center (or process segment). At the work cells, the tasks can be selected online (e.g. touch screen) and the task list updated in realtime.
   b. *Purely manual by the production manager:* With the information he gets from the control point, the production manager creates a weekly production schedule and task lists for each shift. Work orders and shift schedules are distributed on the production floor in paper format. By walking the process and observing the production progress, the production manager continuously adjusts the schedule to follow the changing conditions of the production environment.

Because of its nature, most of the communication flow needs to be collected manually. Nevertheless, depending on the implementation level of MES, some information could be extracted from the ISA 95 models to indicate the frequency of the information exchange:

- Push system: The frequency of the creation of a detailed production schedule or update of the task list at production execution can be determined.
- Pull system: In the case of electronic pull production control, the flow of kanban cards can be visualized.
- Supplier: The frequency of raw material transports can be calculated by analyzing material arrival times at the beginning of the value stream.

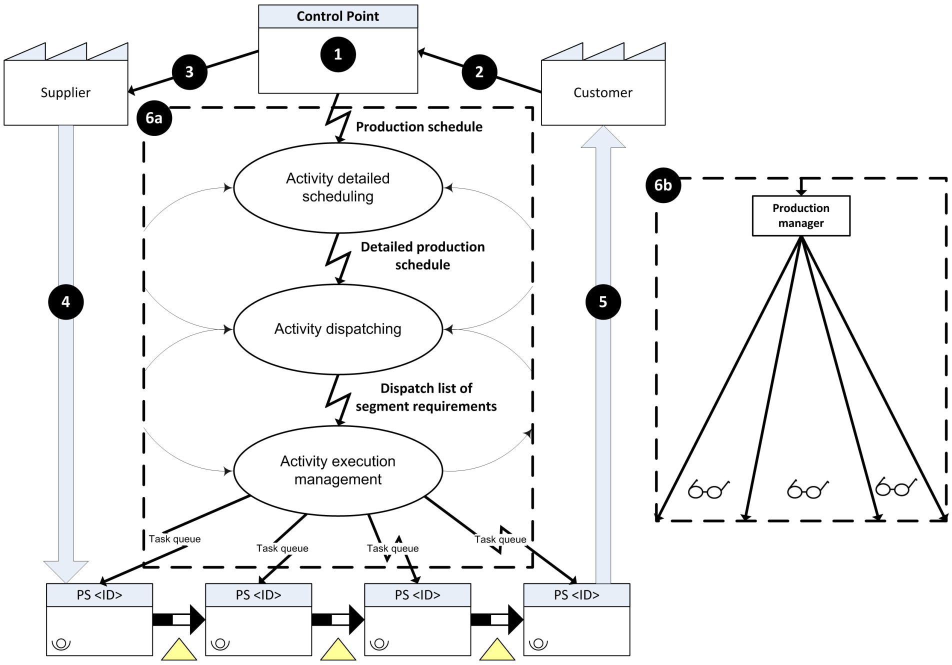



*Figure A.9: The different aspects of the communication flow of the value stream in case of a typical push production environment*

– Customer: The leave times of final products at the end of the value stream can give an indication of customer transport frequency.

The last compartment of the map is the timeline drawn at the bottom of the map. Based on the cycle times of the process boxes and the inventory times in between, the timeline can be documented and the important map values; such as PLT, TCT and RVA time; can be computed by using available MES information. If there are parallel flow paths then the longest path is described on the timeline.

All information about the structure of the current state map is bundled by an umbrella *process segment*. General information; such as time frame of analysis, mapped product family, required general performance values (e.g. PLT), etc.; are listed as extra parameters. Figure A.11 shows how the umbrella process segment is defined as a collection of all process segments associated with the different tasks in the value stream. The structure of the map is defined by the sequence of the different process segments and their dependencies.

3. **Collect and map the basic information about the current state**
In an attempt to facilitate Lean information management within MES, a pull-based information flow was initiated in the above description. The information requirements for aVSM (part of activity *performance analysis*) resulted in

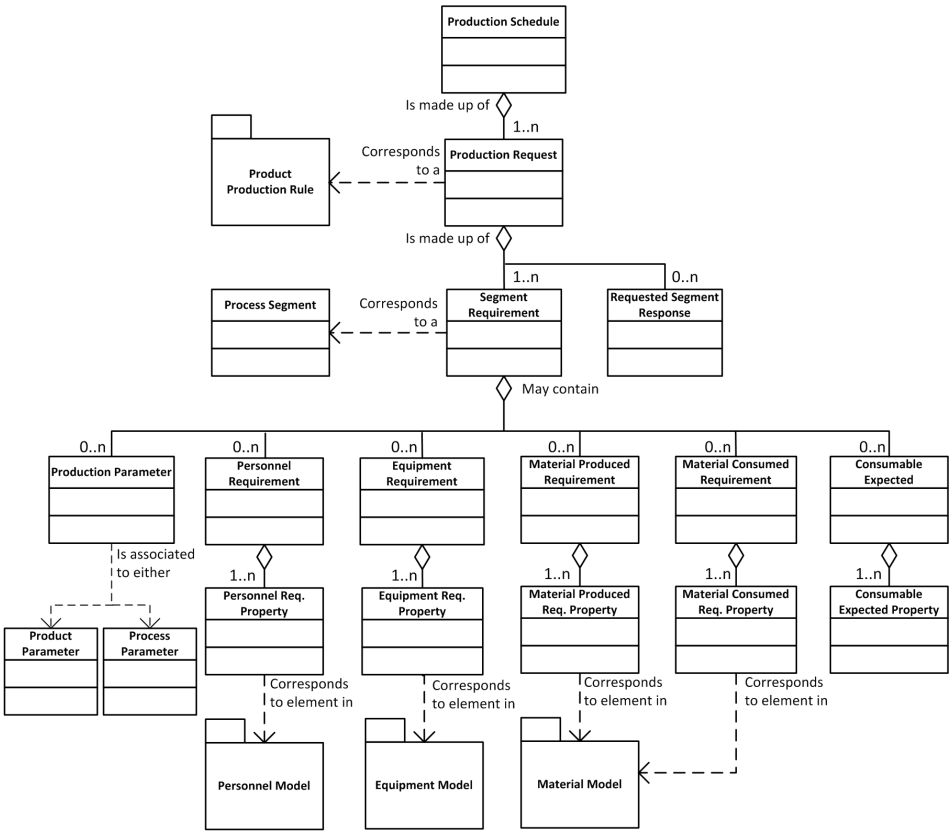



*Figure A.10: The production schedule model of ISA 95 provides a standard terminology for all information concerning the scheduling of production orders (Source: ISA 95 (2000))*

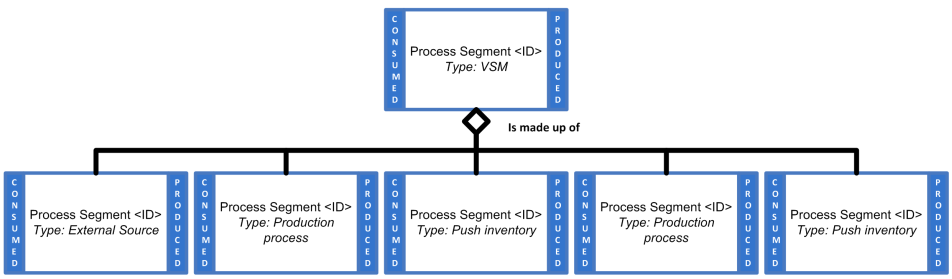



*Figure A.11: An umbrella process segment bundles the structure and information of the current state map*

information requests to other MOM activities; such as *resource management*, *definition management* and *tracking*. To be able to generate the necessary information, each activity, for its part, requests data from the activity *data* *collection* to populate its model structure. For *tracking* purposes, segment responses must be created for each executed task. This information is delivered to data collection by the activity *execution management*. When a time frame of historical data is already available, then the necessary calculations (see algorithm 6) can be performed. Computed values are automatically updated on the map, missing values leave blanks that can be filled in manually on the map. However, the ISA 95 model structure was modified in such a way that future data collection will enable automated calculations for the next mapping exercise.

```
procedure MAPBASICINFORMATION(umbrella process segment)
    for all process segments connected to umbrella process segment do
        for all parameters in process segment definition do
            if historical data available in segment responses then
                Calculate value with defined formula OR read value if already available
                Add information to the map
            else
                Add empty box to the map (to add value later during manual analysis)
            end if
        end for
    end for
end procedure
```

*algorithm 6: Add the basic information on the value stream map*

The result of these steps is a current state map of the value stream conform the standard mapping rules. The available historical information within MES is structured on the map. Missing values are indicated and can be added later on during the manual efforts. A good integration within MES imposes standard work during the VSM analysis. The model requirements for ISA 95, to structure the data support, were emphasized. A number of situations were already mentioned where ISA 95 object models were modified to collect extra manufacturing information to support future VSM exercises. In section 3.4 the role of these change management efforts will be further described.

### A.1.4 Future state mapping

Just as the current state map is a visual representation of the process as it actually operates today, the future state map is intended to indicate how the value stream could operate more efficiently. The future state map is a blueprint for change. The human input is the driving force of this exercise, in order to identify and remove the waste on the current state map. Brainstorming sessions must result in a future state map, showing the new situation and the necessary changes to achieve it. The *kaizen burst* icon shows what must be done to make each change a reality. A number of key actions guide the analysis toward the future state (Rother and Shook, 1999). For each action, the proposed ISA 95 representation is

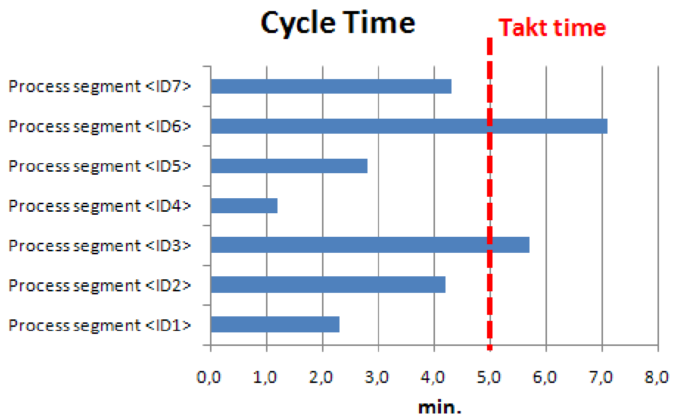



*Figure A.12: An example of a line balancing chart of a poorly balanced value stream*

discussed. The related model state changes to incorporate the modified production control are listed in section 3.4.

1. **Produce to takt time:** The production rhythm or takt time is determined by customer demand. The average daily customer demand (e.g. determined by forecast) can be entered manually in support of the analysis or - e.g. in case of stable demand - can be calculated based on historical data of final products produced. In a line balancing chart (Figure A.12), the calculated process cycle times are plotted in combination with the takt time. Based on this information, two critical questions can be answered:

   - Is the value stream capable of meeting customer demand?
   - Is the value stream balanced?

   The goal of balancing and pacing the flow of the value stream is to have all cycle times less than the takt time, to be able to meet customer demand. In addition, all cycle times must be as equal as possible. The value stream may never be perfectly balanced. Therefore, the team must keep looking for ways to further balance it in the future. An optimization can be achieved by eliminating ('X' out the step), restructuring (e.g. merge multiple tasks) and optimizing (e.g. remove wasteful activities) processes, modifying product flow, etc. Figure A.12 depicts a situation where neither of the two conditions listed above are met. The cycle times of process segments <ID3> and <ID6> must be reduced below the five minutes to make the value stream capable of meeting customer demand.

2. **Develop continuous (one-piece) flow:** An attempt is made to achieve a continuous (one-piece) flow of materials in the rebalanced value stream. Just like all other

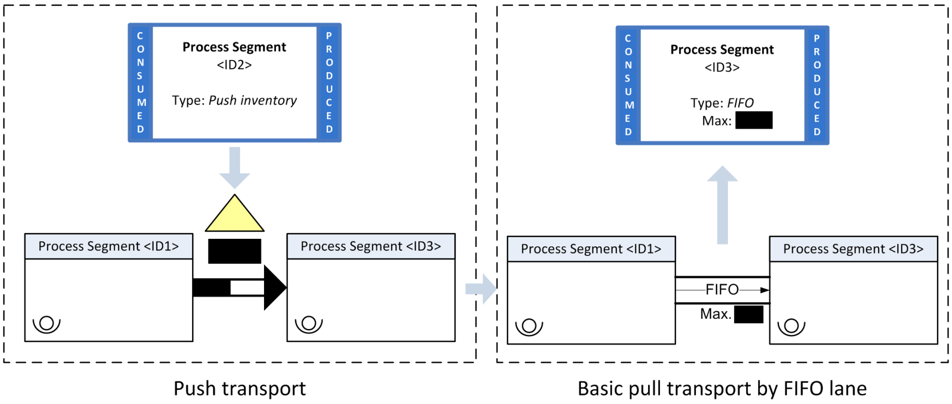



*Figure A.13: The transition from push inventory to FIFO lane in ISA 95 terminology*

value stream waste, inventory times must be reduced to a minimum. However, as identical cycle times for all processes at all time - theoretically, the optimal situation - is not realistic, the complete elimination of in-process inventory will only be a utopia. The most basic form to ensure continuous flow is a FIFO lane. It ensures that the oldest work flowing into the area is the first work to receive value-added activity and be completed, before working on any other WIP waiting. It is common to limit the amount of work that can sit in the FIFO lane at any given moment in time. That is indicated by a maximum number of units of work. In this way, reaching the maximum amount signals possible problems downstream, triggering operators to investigate problems and react appropriately. FIFO lanes can be best compared to the use of conveyors, where product sequence is maintained and capacity is limited (depending on product size and conveyor length). In an extremely balanced value stream, all existing inventory locations (push flow within the current state map) could be transformed to FIFO lanes. This transport is represented by a *process segment* of type *FIFO* and contains a maximum value for the amount of work, as an extra parameter. Production is not longer centrally controlled, but control is distributed locally. The FIFO lane determines the production of the upstream process. While the FIFO work content is lower than the listed maximum value, the upstream process may keep producing products. Figure A.13 gives the representation of the FIFO lane in ISA 95 terminology.

3. **Use supermarkets where necessary:** The use of a FIFO lane is a good choice when the cycle time of the downstream process is less than or equals the cycle time of the upstream process. If there is a wide range of cycle times, then a supermarket must be added to ensure that work can continue to flow. Where one-piece flow is not possible, kanban cards can be used to pull the correct amount of products at the right time. Supermarkets must be placed after processes with extremely short cycle times, a high product mix or delivering to multiple downstream processes.

Important information on the kanban cards is: Card ID, container size, material description, supplier process and customer process. In section 2.2, the formula to calculate the number of kanban cards was given by equation 2.2. A perfect number of cards does not exist. Depending on the changing conditions (average demand, demand variability, kanban lead time), the amount of cards must be continuously recalculated and adjusted in order to reduce inventory. Figure A.14 shows how a supermarket and a (production) kanban replenishment loop can be structured using ISA 95 terminology. The functionality of a kanban card is similar to that of the *segment requirement* of the *production schedule* model. The card ID, material description and the container size are defined by standard attributes *ID*, *material definition*[3] and the *quantity* of the *material produced requirement* of the segment requirement. The *segment* attribute of the segment requirement corresponds to the supplier *process segment*. The *Location* attribute of the material produced requirement specifies the customer *process segment*, being the end point of the kanban card. The supermarket is represented by a *process segment* of segment type *supermarket*. Each *production request* groups the kanban cards of the same material. The number of kanbans must be listed as an additional property. Each activity in the supermarket results in the creation of a *segment response*. Each segment response relates to a corresponding segment requirement (kanban card). That segment response has also a link to the actual products in the container, associated with the kanban card through the *material produced actual* objects. The waiting kanban cards are listed at each process. The kanban list can be organized, e.g. following the kanban wall principle[4] in order to determine the kanban priority. The *production schedule* presents the wall structure with columns (different production requests or card types) and rows (different segment requirements or kanban cards).

CONWIP is a pull system alternative to kanban that is applicable in high product mix environments[5]. A constant WIP is maintained on the production floor. The representation of this control system within ISA 95 is a special case of the supermarket description given above. The production kanban loop now runs through the entire value stream. A constant number of CONWIP cards or *segment requirements* is maintained in the value stream. Only when a (a container of) final product(s) is finished, a new segment requirement can be launched at the beginning of the value stream.

4. **Schedule based on the pacemaker:** In a pull system, the single process step in the value stream that determines the speed of the process is known as the *pacemaker*. In a perfectly balanced and flowing value stream, whatever speed the pacemaker

[3] As a generic kanban card is not linked to a specific product (but rather a process capability), a material class indication can be used in that case.

[4] The number of kanbans for each product is counted and the most urgent material requests are produced first. The minimum batch size can be taken into account to prioritize the requests.

[5] The latest addition is Paired-cell Overlapping Loops of Cards with Authorization (POLCA) (Suri, 2003), an extended version of CONWIP that not only regulates the WIP in the whole value stream, but also controls the workload for each individual process.

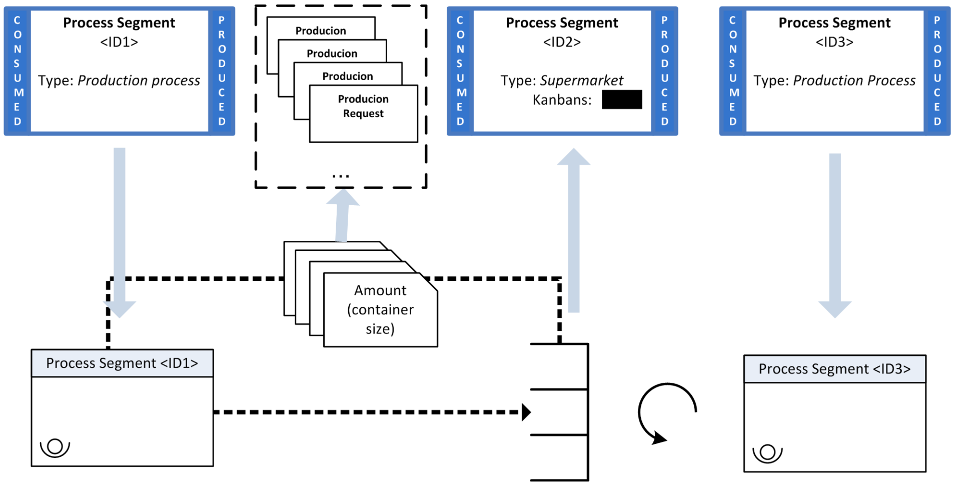



*Figure A.14: The representation of a supermarket with (production) kanban loop in ISA 95 terminology*

performs at is the speed that all other steps in the value stream must perform at. The pacemaker is the process where the flow stops and pull begins. That means only one process must be scheduled. The communication flow described in figure A.9 can be used, but this time only to control one process segment. That strongly simplifies the production control. For pure pull system value streams, the pacemaker should be placed as close to the very end of the process flow as possible. In customized production settings, the pacemaker is often found much more upstream, usually the last point of commonality.

5. **Level the production mix at the pacemaker:** Load leveling is used to manage the mix of products to be produced. When a value stream produces multiple products, there must be a method to make sure that the right thing is being worked on at the right time. The icon is drawn on top of the pacemaker process. A note may be added above or below to assist in the prioritizing strategy.

6. **Level the production volume:** Establishing a consistent or level production pace creates a predictable production flow. A good place to start is to regularly release only a small, consistent amount of production instructions at the pacemaker process, and simultaneously take away an equal amount of finished goods. This practice is called 'paced withdrawal'. The consistent increment of work is called the pitch. The pitch increment is calculated based on packout container quantity (the number of parts one container of finished goods holds) or a multiple or fraction of that quantity. For example, if your takt time is 30 seconds and your pack size is 20 pieces, then your pitch is 10 minutes. That means that every 10 minutes, the pacemaker process must be given the instruction to produce one pack quantity. In

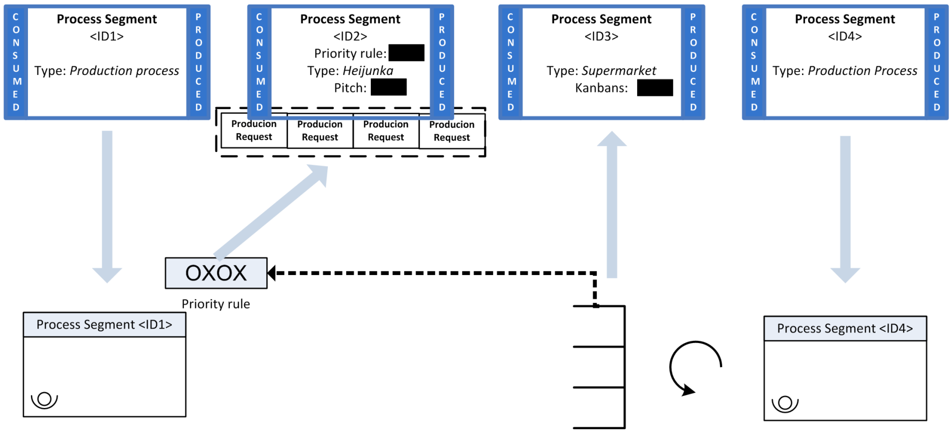



*Figure A.15: An ISA 95 compatible representation of load leveling*

addition, one finished pitch quantity is taken away. A tool used to help level both the mix and volume of production is a load leveling (or heijunka) box. A physical load leveling box has a column of kanban slots for each pitch interval and a row of kanban slots for each product type. Kanban cards are placed (loaded) into the leveling box in the desired mix sequence by product type. The material handler then withdraws those kanban cards and brings them to the pacemaker process - one at a time, at the pitch increment. Figure A.15 shows an ISA 95 compatible representation of load leveling. A process segment of type *heijunka* gets additional properties for the *pitch* value and the *priority rule*. At pitch frequency, the next production request - containing a mix of segment requirements (kanban cards) - of the heijunka box is activated.

7. **Every Part Every (EPE) 'time period':** By shortening change-over times and running smaller batches in your upstream processes, those processes will be able to respond to changing downstream needs more quickly. In turn they will require even less inventory to be held in their supermarkets. In general, the batch sizes or EPE are noted in the data boxes. EPE stands for 'every part every ...' after which a time such as week, day, shift, hour, pitch, or takt must be added. This describes how frequently a process changes over to produce all part variations. An initial goal at many plants is to make at least 'every part every day' for high-running part numbers. This value strongly depends on the change-over times of the process. As a general rule, 10% of available time is reserved for change-overs.

8. **Process improvements:** To reflect the proposed improvements for the future state, kaizen bursts are added to the map. A number of typical improvements are listed for each process segment type in appendix A. A kaizen burst triggers a PDCA cycle in order to achieve the documented improvement.

By following the above steps, a future state map can be constructed in MES. If aVSM has VSM simulation functionality (Lian and Van Landeghem, 2007), then the effect of the new value stream can be simulated by using historical data from MES.

### A.1.5 Lean implementation

A Lean implementation plan is initiated in order to achieve the documented future state. If the new state is introduced on the production floor, then MES must fully incorporate these changes in order to support the new way of working. By performing an appropriate sequence of standard change work flows, MES support for the future state can be achieved. Typical kaizen bursts are added to the map stating important (follow-up) actions. The change management approach to enable these Lean changes is presented in section 3.4. The migration of the ODS to the future state will provide all MOM activities with the necessary information for the newly introduced production control. When the downstream inventory control of a production process is of the type *Push inventory*, then the communication flow for a typical push environment (figure A.9) will define the actions for the MOM activities. In case of pull production control, activity tasks will be adjusted. Section A.4 provides a detailed description of some pull configurations.

### A.1.6 Follow up Lean progress

The change management of MES does not only support the new way of working. It also enables MES to redraw the current state when (part of) the Lean changes are implemented. The given VSM representations of the typical current state (Push) and future state (Pull) value stream by ISA 95, make it possible to support the construction of VSM at all times, also for hybrid situations (to assess intermediate results). After a certain period of time, the current state map can be redrawn. That enables an evaluation of the new way of working and - where necessary - further changes can be introduced. The Lean planning system and the performance evaluation are closely integrated to achieve an efficient Lean transformation.

| Attribute name | Description | Example |
|---|---|---|
| **ID** | A unique identification of a process segment, within the scope of the information exchanged (production capability, production schedule, production performance, ...). The ID shall be used in other parts of the model when the process segment needs to be identified, such as the production capability for this segment, or a production response identifying the segment. | *Assembly* |
| **Description** | Additional information about the process segment. | *The assembly operation of final boxes* |
| **Location** | An identification of the associated element of the equipment hierarchy model. Optionally defines the scope of the process segment definition, such as the site or area it is defined for. | *CharBox Production* |
| **Element Type** | A definition of the type of the associated element of the equipment hierarchy model. | *Site* |
| **Published Date** | The date and time on which the process segment was published or generated. | *2010-11-12 13:55* |
| **Duration** | Duration of process segment, if known. | *3.94* |
| **Duration Unit of Measure** | The units of measure of the duration, if defined. | *Minutes* |

*Table A.6: The standard attributes of the process segment object (Source: ISA 95 (2000))*

## A.2 Value stream mapping icons

Tables A.2, A.3 and A.4 gave an overview of the ISA 95 representation of the different components of a value stream map. The tasks or activities linked within the value stream (as well material as information flow) are represented by process segment objects (Figure A.16). Table A.6 lists the standard attributes of the process segment object. Additional properties are configured by process segment parameters (Table A.7). The structure of the value stream is defined by process segment dependencies (Table A.8). Kanban cards are represented by segment requirement objects (Figure A.17). Cards with the same material description are grouped by a production request object (Kanban card type). A production schedule object contains all production request objects at one location (e.g. kanban post, queue or wall). Table A.9 lists the standard attributes of the segment requirement object. The material type and container size of the kanban card are defined within the material produced requirement (Table A.10) of the segment requirement. As an overall example, (part of the) ISA 95 representations are listed for the current (Figure 2.7) and future (Figure 2.8) state map of the CharBox company, as presented in section 2.2. Table A.11 lists the basic map information and table A.12 the structure of the current state map. Table A.14 illustrates the representation of the future state map information. Table A.15 represents an example of the kanban card signals and locations. Table A.13 lists a number of typical examples of kaizen bursts.

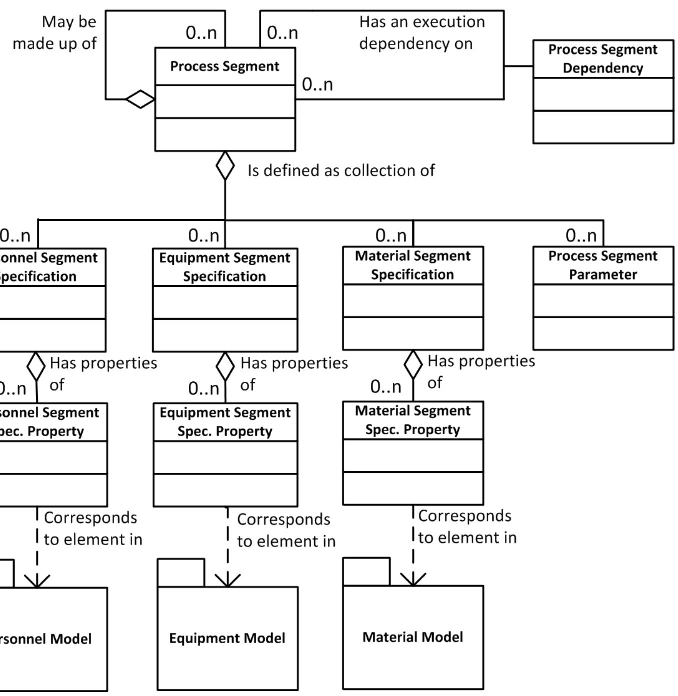



*Figure A.16: The process segment model of ISA 95 provides a standard terminology for all tasks or activities linked within the value stream (Source: ISA 95 (2000))*

| Attribute name | Description | Example |
|---|---|---|
| **Name** | Name of the process segment parameter for a specific process segment. | *Type* |
| **Description** | Contains additional information of the process segment parameter. | *Defines the specific type of the operation* |
| **Value** | The value, set of values, or range of acceptable values | {*'Production Process', 'Push Inventory', 'Supermarket', 'Manual Communication' etc.*} |
| **Unit of Measure** | Unit of measure of the values, if applicable. | |

*Table A.7: The process segment parameters make it possible to add extra VSM information to the process segment objects (Source: ISA 95 (2000))*

| Attribute name | Description | Example |
|---|---|---|
| **Description** | Contains additional information and descriptions of the process segment dependency definition for a specific process segment. | *Defines the operation sequence of the current state map* |
| **Dependency type** | Defines the execution dependency constraints of one segment by another segment. Examples of these constraints, using A and B to identify the segments, or specific resources within the segments, and T to identify the timing factor, include: B can not follow A; B may run in parallel to A; B may not run in parallel to A; Start B at A start; Start B no earlier than T after A start; etc. | *Aluminum Cutting* follows *Standard Sheet Warehouse* |
| **Timing factor** | Timing factor used by dependency | |
| **Time Unit of Measure** | The units of measure of the timing factor, if defined. | |

*Table A.8: The process segment dependencies make it possible to add the structure of the tasks within the value stream map of the product family (Source: ISA 95 (2000))*

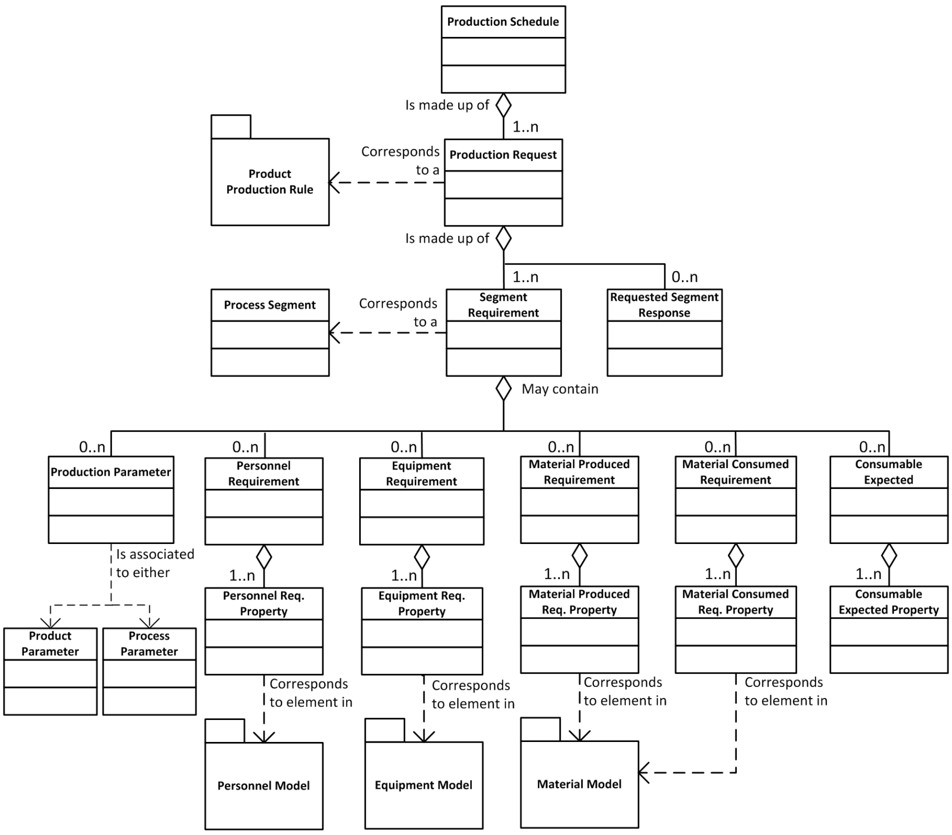



*Figure A.17: The segment requirement object (of the production schedule model of ISA 95) provides a standard terminology for the representation of kanban signals within the value stream (Source: ISA 95 (2000))*

| Attribute name | Description | Example |
|---|---|---|
| **ID** | A unique identification of the segment requirement or kanban card ID. | A67 |
| **Segment** | An identification of the process segment associated with the segment requirement or the supplier process of the kanban loop. | *Aluminum Cutting* |
| **Description** | Contains additional information and descriptions of the segment requirement. | *Kanban card signaling production for the Aluminum Cutting process* |
| **Earliest Start Time** | The expected earliest start time of this segment requirement, if applicable. | |
| **Latest End Time** | The expected latest end time of this segment requirement, if applicable. | |
| **Duration** | The expected duration of this segment requirement, if applicable. Note, this should match the associated process segment duration. | |
| **Duration Unit of Measure** | The unit of measure of the duration, if applicable. | |

*Table A.9: The standard attributes of the segment requirements object are used to represent a kanban card (Source: ISA 95 (2000))*

| Attribute name | Description | Example |
|---|---|---|
| **Material Class** | Identifies the associated material class or set of material classes of the requirement for a specific segment requirement. (Used in case of a generic Kanban which can represent a whole product family.) | |
| **Material Definition** | Identifies the associated material definition or set of material definitions of the requirement for a specific segment requirement. | *Sheet format box A* |
| **Material Lot** | Identifies the associated material lot, or set of material lots of the requirement for a specific segment requirement. | |
| **Material Sublot** | Identifies the associated material sublot, or set of material sublots of the requirement for a specific segment requirement. | |
| **Description** | Contains additional information and descriptions of the material produced requirement definition. | *Kanban card material description* |
| **Location** | Identifies the proposed location of the produced material or the customer process of the kanban loop. | *Sheet Warehouse* |
| **Quantity** | Specifies the amount of material to be produced, if applicable. Applies to each member of the material lot, materials definition, or material class sets. Represents the container size of the kanban card. | 10 |
| **Quantity Unit of Measure** | Identifies the unit of measure of the quantity if applicable. | *Sheets* |

*Table A.10: The standard attributes of the material produced requirement object are used to respresent kanban card information (Source: ISA 95 (2000))*

| Process Segment | | Process Segment Parameters (* standard attr.) | | |
|---|---|---|---|---|
| **ID** | **Description** | **Name** | **Value** | **Unit of Measure** |
| **Current State** | Umbrella object for the current state map | Type | VSM | |
| | | Production Control | MRP II | |
| | | PLT | 27.37 | days |
| | | TCT | 18.93 | minutes |
| | | RVA | 0.144 | % |
| **Supplier** | The supplier of the value stream | Type | External Source | |
| **Supplier Delivery** | Characteristics of the supplier deliveries | Type | Delivery | |
| | | By | Truck | |
| | | Frequency | 1 | /week |
| **Receiving** | Handling of incoming raw materials | Type | Production Process | |
| | | Operators | 2 | persons |
| | | C/T | 1.5 | minutes |
| | | C/O | 5.1 | minutes |
| | | U/T | 100 | % |
| | | Distance | 250 | meters |
| | | Task List | Receiving Schedule | |
| **Standard Sheet Warehouse** | Inventory location for standard sheets | Type | Push Inventory | |
| | | Duration* | 1200 | pieces |
| | | Distance | 68 | meters |
| **Aluminum Cutting** | Cutting of standard sheets in different formats | Type | Production Process | |
| | | Operators | 2 | persons |
| | | C/T | 0.7 | minutes |
| | | C/O | 8.3 | minutes |
| | | U/T | 85 | % |
| | | Distance | 3 | meters |
| | | Task List | Aluminum Cutting Schedule | |
| **Sheet Warehouse** | Inventory location for sheet format | Type | Push Inventory | |
| | | Duration* | 850 (1) & 350 (2) | pieces |
| | | Distance | 23 (1) & 133 (2) | meters |
| **Box Folding** | Folding of the boxes | Type | Production Process | |
| | | Operators | 3 | persons |
| | | C/T | 3.75 | minutes |
| | | C/O | 0 | minutes |
| | | U/T | 95 | % |
| | | Distance | 5 | meters |
| | | Task List | Box Folding Schedule | |
| **Folded Box Warehouse** | **SIMILAR AS ABOVE** | | | |
| **Box Welding** | | | | |
| **Preassembly Warehouse** | | | | |
| **Character Punching** | | | | |
| **Assembly** | | | | |
| **Assembled Box Warehouse** | | | | |
| **Packaging** | | | | |
| **Final Box Warehouse** | | | | |
| **Shipping** | | | | |
| **Customer Delivery** | | | | |
| **Customer** | | | | |
| **Supplier Orders** | Monthly forecast & weekly orders | Type | Electronic Communication | |
| **Customer Orders** | Monthly forecast & weekly orders | Type | Electronic Communication | |
| **Weekly Schedule** | Weekly schedule | Type | Electronic Communication | |
| **Production Manager** | Production manager | Type | Label | |
| **Daily Schedule 1-6** | Daily schedule | Type | Manual Communication | |

*Table A.11: The different process segments for the current state map of CharBox as mapped in figure 2.7*

| Process Segment | Dependency Type | Process Segment |
|---|---|---|
| Supplier Delivery | follows | Supplier |
| Receiving | follows | Supplier Delivery |
| Standard Sheet Warehouse | follows | Receiving |
| Aluminum Cutting | follows | Standard Sheet Warehouse |
| Sheet Warehouse | follows | Aluminum Cutting |
| Box Folding | follows | Sheet Warehouse |
| Character Punching | follows | Sheet Warehouse |
| ETC. | | |
| Weekly Schedule | follows | Current State |
| Production Manager | follows | Weekly Schedule |
| Daily Schedule 1 | follows | Production Manager |
| Aluminum Cutting | follows | Daily Schedule 1 |
| ETC. | | |

*Table A.12: The different process segment dependencies for the current state map of CharBox as mapped in figure 2.7*

| Process Segment | Kaizen burst description |
|---|---|
| Production process | Reduce C/T under X minutes |
| | Reduce C/O by SMED |
| | Increase U/T by TPM |
| | Reduce defects by TQM |
| Pacemaker | Level production volume and mix |
| Supplier | Improve pull system integration with supplier |
| Supermarket | Reduce container size |
| | Reduce number of cards |
| FIFO | Refine maximum content |

*Table A.13: Examples of typical kaizen bursts for each process segment type*

| Process Segment | | Process Segment Parameters (* standard attr.) | | |
|---|---|---|---|---|
| **ID** | **Description** | **Name** | **Value** | **Unit of Measure** |
| **Future State** | Umbrella object for the future state map | Type | VSM | |
| | | Production Control | MES | |
| | | PLT | 2.16 | days |
| | | TCT | 18.93 | minutes |
| | | RVA | 1.86 | % |
| | | Kaizen1 | Digitize kanban system to reduce waiting times | |
| **Supplier** | The supplier of the value stream | Type | External Source | |
| | | Kanban List | Supplier Kanban Post | |
| **Supplier Delivery** | Characteristics of the supplier deliveries | Type | Delivery | |
| | | By | Truck | |
| | | Frequency | 3 | /day |
| | | Kaizen2 | Improve pull system integration with supplier by reducing lead time | |
| **Raw Material Supermarket** | Inventory location for supplier deliveries | Type | Supermarket | |
| | | Duration* | 7x15 | pieces |
| | | Kanban List | Raw Material Supermarket Kanbans | |
| | | Kaizen3 | Setup supermarket and kanban | |
| **Receiving** | Handling of incoming raw materials | Type | Production Process | |
| | | Operators | 2 | persons |
| | | C/T | 1.5 | minutes |
| | | C/O | 5.1 | minutes |
| | | U/T | 100 | % |
| | | Distance | 250 | meters |
| | | Task List | Receiving Kanbans | |
| **Standard Sheet Supermarket** | Inventory location for standard sheets | Type | Supermarket | |
| | | Duration* | 2x15 | pieces |
| | | Kanban List | Standard Sheet Supermarket Kanbans | |
| | | Kaizen4 | Setup supermarket and kanban | |
| **Aluminum Cutting** | Cutting of standard sheets in different formats | Type | Production Process | |
| | | Operators | 2 | persons |
| | | C/T | 0.7 | minutes |
| | | C/O | 5 | minutes |
| | | U/T | 95 | % |
| | | Distance | 3 | meters |
| | | Task List | Aluminum Cutting Kanbans | |
| | | Kaizen5 | Reduce C/0 to $\leq 5$ | |
| | | Kaizen6 | Improve U/T to $\geq 95$ | |
| **Aluminum Cutting** | **SIMILAR AS ABOVE** | | | |
| **Sheet Supermarket** | | | | |
| **Box Folding** | | | | |
| **FIFO Folded Boxes** | | | | |
| **Box Welding** | | | | |
| **Preassembly Supermarket** | | | | |
| **Character Punching** | | | | |
| **Assembly** | | | | |
| **FIFO Final Boxes** | | | | |
| **Packaging&Shipping** | | | | |
| **Customer Delivery** | | | | |
| **Customer** | | | | |
| **Customer Orders** | | | | |
| **Pacemaker Control** | | | | |

*Table A.14: The different process segments for the future state map of CharBox as mapped in figure 2.8*

*Table A.15: A representation example of the kanban definitions for the future state map of CharBox as mapped in figure 2.8*

| Production Schedule | Production Request | Segment Requirement | | | Material Produced Requirement | | |
|---|---|---|---|---|---|---|---|
| **ID** | **ID** | **ID** | **Material Definition** | **Segment** | **Quantity** | **Unit of Measure** | **Location** |
| **Supplier Kanban Post** | **Raw Material Kanbans** | RM01 | Supplier package | Supplier | 15 | sheets | Raw Material Supermarket |
| | | RM02 | Supplier package | Supplier | 15 | sheets | Raw Material Supermarket |
| **Raw Material Supermarket Kanban** | **Raw Material Kanbans** | RM03 | Supplier package | Supplier | 15 | sheets | Raw Material Supermarket |
| | | RM04 | Supplier package | Supplier | 15 | sheets | Raw Material Supermarket |
| | | RM05 | Supplier package | Supplier | 15 | sheets | Raw Material Supermarket |
| | | RM06 | Supplier package | Supplier | 15 | sheets | Raw Material Supermarket |
| | | RM07 | Supplier package | Supplier | 15 | sheets | Raw Material Supermarket |
| **Receiving Kanbans** | **Standard Sheet Kanbans** | SS01 | Standard Sheet | Receiving | 15 | sheets | Standard Sheet Supermarket |
| **Standard Sheet Supermarket Kanbans** | **Standard Sheet Kanbans** | SS02 | Standard Sheet | Receiving | 15 | sheets | Standard Sheet Supermarket |
| **Aluminum Cutting Kanbans** | **Sheet Format A Kanbans** | SFA01 | Sheet Format A | Aluminum Cutting | 10 | sheets | Sheet Supermarket |
| | **Sheet Format B Kanbans** | SFB01 | Sheet Format B | Aluminum Cutting | 10 | sheets | Sheet Supermarket |
| | **Sheet Format Char Kanbans** | SFC01 | Sheet Format Char | Aluminum Cutting | 40 | sheets | Sheet Supermarket |
| **Sheet Supermarket Kanbans** | **Sheet Format A Kanbans** | SFA02 | Sheet Format A | Aluminum Cutting | 10 | sheets | Sheet Supermarket |
| | **Sheet Format B Kanbans** | SFB02 | Sheet Format B | Aluminum Cutting | 10 | sheets | Sheet Supermarket |
| | **Sheet Format Char Kanbans** | SFC02 | Sheet Format Char | Aluminum Cutting | 40 | sheets | Sheet Supermarket |
| | | SFC03 | Sheet Format Char | Aluminum Cutting | 40 | sheets | Sheet Supermarket |
| **Box Folding Kanbans** | **Box Kanbans** | BA01 | Box A | Box Folding | 10 | boxes | Preassembly Supermarket |
| **Box Welding Kanbans** | **Box Kanbans** | BB01 | Box B | Box Folding | 10 | boxes | Preassembly Supermarket |
| **Character Punching Kanbans** | **Char Kanbans** | C01/01 | Char01 | Character Punching | 10 | characters | Preassembly Supermarket |
| | | C07/01 | Char07 | Character Punching | 10 | characters | Preassembly Supermarket |
| | | C16/01 | Char07 | Character Punching | 10 | characters | Preassembly Supermarket |
| | | C33/01 | Char07 | Character Punching | 10 | characters | Preassembly Supermarket |
| **Preassembly Supermarket Kanbans** | **Box Kanbans** | BA02/BB02 | Box A/B | Box Folding | 10 | boxes | Preassembly Supermarket |
| | **Char Kanbans** | <the rest> | Char01-40 | Character Punching | 10 | characters | Preassembly Supermarket |

## A.3 Definition of typical VSM facts and calculations

Typical VSM facts and calculations can be predefined in the Lean MES framework. Adding a new fact (or KPI) to a resource, triggers a change work flow that restructures the ODS in order to support the calculation of that new information. How these KPI formulas and calculations can be defined in form of ISA 95 models in the ODS is currently not standardized. However, part 4 of ISA 95 covers internal MOM transactions and - when published - should come up with a standard solution. For a number of typical VSM facts, the calculation method based on standard ISA 95 models is listed.

- Cycle time - C/T: The average time between the production of two subsequent good products. This value can be calculated for each process segment by dividing the total production time by the total number of good products produced by the process segment within the time frame of the data analysis (A.3).

$$C/T = \frac{\sum_{i=0}^{n-1} (E_i - S_i)}{\sum_{i=0}^{n-1} \sum_{j=0}^{m-1} Q_{i,j}} \tag{A.3}$$

with

$$\begin{aligned}
n &= \text{Number of segment responses of activity type } \textit{production run} \\
E_i &= \text{Actual end time of segment response } i \\
S_i &= \text{Actual start time of segment response } i \\
m &= \text{Number of material produced actual objects of segment response } i \\
Q_{i,j} &= \text{Quantity of material produced } j \text{ of segment response } i
\end{aligned}$$

- Change-over time - C/O: The average time between production runs, required to set up a machine/process. The time is measured from the last good product of the previous production run, till the first good product of the new production run. This value can be calculated by taking the average of all setup times [6] within the time frame of the data analysis (A.4).

[6]This calculation method assumes that the end time of the segment response object of the setup runs till the first good product of the following production run.

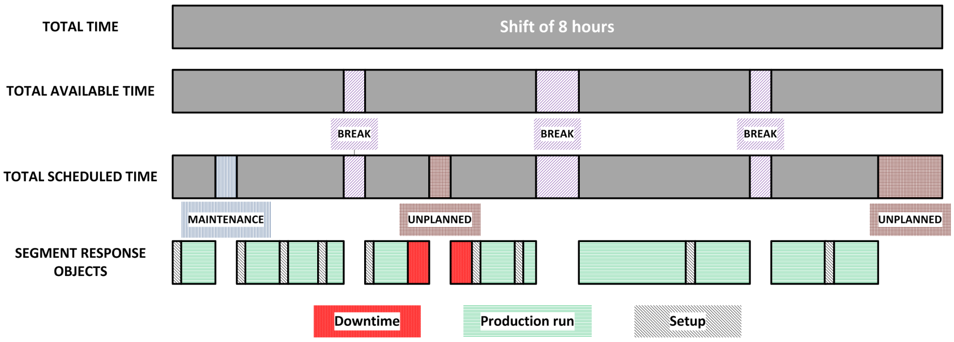



*Figure A.18: An example of how the different segment response objects must add up to the total scheduled time during one shift for each process segment*

$$C/O = \frac{\sum_{i=0}^{n-1} (E_i - S_i)}{n} \tag{A.4}$$

with

$n$ = Number of segment responses of activity type *setup*

$E_i$ = Actual end time of segment response $i$

$S_i$ = Actual start time of segment response $i$

- Uptime - U/T: The percentage of time that a piece of equipment works properly when the operator uses it for the prescribed task. This is also described as the reliability of the equipment. Planned downtimes (e.g. maintenance or breaks) are not taken into account. This value is calculated as the ratio between the actual production time and the total scheduled time (A.5). To be able to calculate this ratio using ISA 95 models, all scheduled time of a process segment must result in an appropriate segment response. Figure A.18 illustrates this requirement. Another indication of the total scheduled time can be given by *production capability* objects (Figure A.19). In that case, time spans of all process segment capability objects that were *committed* must be added up.

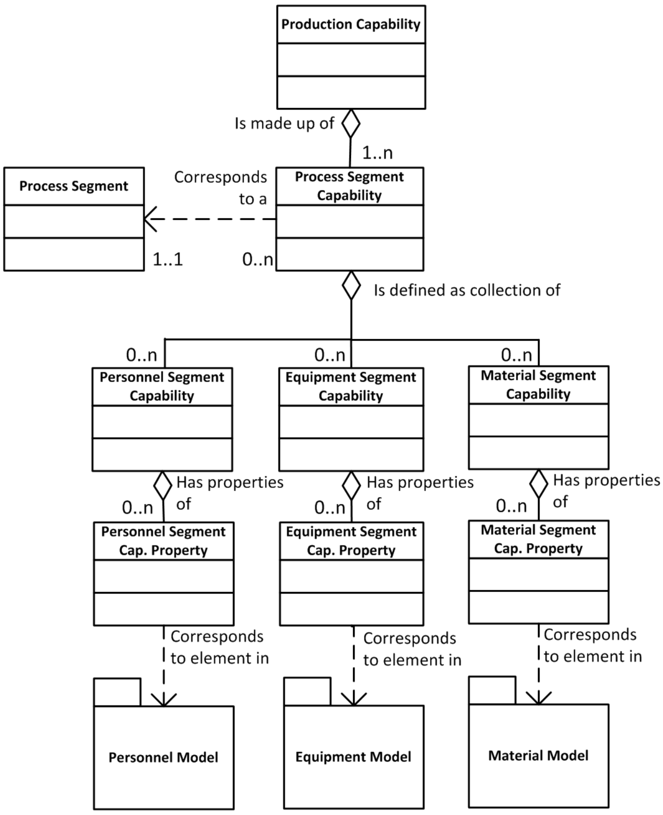



*Figure A.19: The production capability model of ISA 95 provides a standard structure to represent and communicate resource availability information (Source: ISA 95 (2000))*

$$\begin{aligned} U/T &= 100.\frac{\text{actual production time}}{\text{total scheduled time}} \\ &= 100.\frac{\sum_{i=0}^{n-1}(E_i - S_i)}{\sum_{j=0}^{m-1}(E_j - S_j)} \end{aligned} \tag{A.5}$$

with

$n$ = Number of segment responses of activity type *production run*

$m$ = Total number of segment responses

$E_{i/j}$ = Actual end time of segment response $i/j$

$S_{i/j}$ = Actual start time of segment response $i/j$

- Operator count: The number of operators that work in the process segment. That can be an average over a certain time frame. However, the manual method counts the number of operators present at the time of analysis. This information can be delivered by the activity *resource management* that contains the location of all resources and assignment of resources to areas of production.

- Work content - Work content (W/C): The total amount of actual value-added and non-value-added labor time associated with a process. The cycle time denotes the total amount of work to produce one product in a work cell. As multiple operators can perform the production tasks in parallel, this value must be multiplied by the total number of operators in the work cell (A.6) to get the total work content.

$$W/C = n.t_c \tag{A.6}$$

with

$$n = \text{Number of operators}$$
$$t_c = \text{Cycle time C/T}$$

- Defect rate: Defines the ratio of defects to the total number of products produced. A defect is a unit of work that is scrapped or reworked. Each *segment response* of activity type *production run* must specify the value of rejected products - in addition to the value offering the quantity of good products produced, which is a standard attribute of the model. The defect rate is then given by the ratio of defects to the total number of products produced (A.7).

$$\text{Defect rate} = 100.\frac{\sum_{i=0}^{n-1} R_i}{\sum_{i=0}^{n-1} (R_i + Q_i)} \tag{A.7}$$

with

$$n = \text{Number of segment responses of activity type } \textit{production run}$$
$$R_i = \text{Number of rejected products}$$
$$Q_i = \text{Quantity of good products produced}$$

- Availability: The percentage of time that a piece of equipment - shared between two or more value streams - is available for production of products in the value stream being mapped. That equals the share of segment responses belonging to the current value stream (A.8).

$$Avail. = 100.\frac{\sum_{i=0}^{n-1}(E_i - S_i)}{\sum_{j=0}^{m-1}(E_j - S_j)} \quad \text{(A.8)}$$

with

$n$ = Number of segment responses belonging to the current value stream

$m$ = Total number of segment responses

$E_{i/j}$ = Actual end time of segment response $i/j$

$S_{i/j}$ = Actual start time of segment response $i/j$

- Overall Equipment Effectiveness (OEE): The calculation method was given earlier by equation 2.3. Availability reflects the inactivity losses and equals the earlier defined uptime. Quality relates to the earlier defined defect rate and represents the defects losses. Performance incorporates the speed losses by comparing the theoretical time to produce all actual produced products to the actual production time. Therefore the theoretical cycle time, defined within the resource definition of the *process/product segment*, is multiplied by the total number of products produced. The actual production time is set in relation to the total expected production time, in order to calculate the performance percentage (A.9).

$$Performance = 100.\frac{\sum_{j=0}^{n-1}(E_j - S_j)}{\sum_{i=0}^{n-1}Q_i.t_c} \quad \text{(A.9)}$$

with

$t_c$ = Theoretical cycle time of the task

$n$ = Total number of segment responses of activity type *production run*

$Q_i$ = Quantity of good products produced

$E_j$ = Actual end time of segment response $j$

$S_j$ = Actual start time of segment response $j$

- Number of components or parts used at the process step (P/U): This value defines the number of unique parts that are present at the work cell in order to perform all tasks within the value stream. That equals the total number of unique *material consumed actual* objects within all segment responses.

## A.4 Pull production control principles

The migration of the ODS to the future state will provide all MOM activities with the necessary information for the newly introduced production control. When the downstream inventory control of a production process is of the type *Push inventory*, then the communication flow for a typical push environment (figure A.9) will define the actions for the MOM activities. In case of pull production control, activity tasks will be adjusted. A number of pull system configurations and their effect on the activity tasks are described.

1. **FIFO lane** (Figure A.20)

   (a) **Resource management:** The FIFO process segment gets an extra parameter to point to its *production schedule*. That task list has a limited capacity (= 6) and always maintains the FIFO sequence. The schedule contains the task list for the next process downstream. Each task is defined as a segment requirement (= operation) of the production request (= production order).

   (b) **Detailed scheduling:** *No tasks*

   (c) **Dispatching:** When a task is pulled from the FIFO lane (❷), then the remaining segment requirements are shifted to the right.

   (d) **Execution management:** When production process <*ID1*> finishes a task, it enqueues the next segment requirement of the production request as task for the next process downstream (❶). The task is listed in the production schedule of process segment <*ID2*>. Process <*ID1*> can only start a new task, when an empty space is available in the FIFO lane.

   (e) **Data collection:** At the production process and the FIFO lane an identification system (e.g. manual entry, barcode or RFID) is in place to record actions on production orders.

   (f) **Tracking:** A segment response is generated for each action of a process segment. The requested segment response object defines the required structure and information. The start time, end time and other data are delivered by the data collection activity. The possible values for the activity type of the segment response are: production run (execution of the task) and inventory (staying time in the FIFO lane).

   (g) **Performance analyis:** Based on the historical data provided by the segment responses, the optimal value for the maximum number of tasks in the FIFO lane can be recalculated. Equation A.10 shows a possible implementation. This recalculation can be done on a regular basis to react to changing conditions.

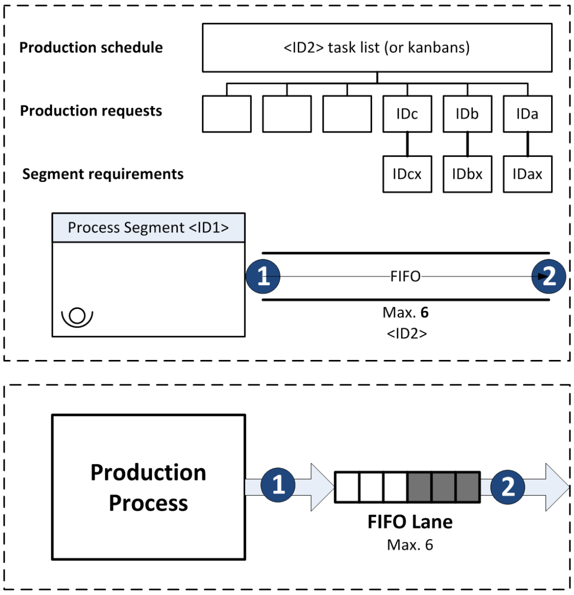



*Figure A.20: FIFO lane configuration in ISA 95*

$$FIFO_{max} = \frac{(MAX_{i=0}^{n}(t_i) - T).Q}{T} \qquad \text{(A.10)}$$

with

$n$ = Number of segment responses belonging to the downstream process segment

$t_i$ = Cycle time of segment response i

$T$ = Takt time

$Q$ = Quantity produced of segment response with maximum cycle time

2. **Supermarket & kanban wall** (Figure A.21)

   (a) **Resource management:** For both process segments (as well production process as supermarket), an extra parameter is defined to point to a *production schedule*. The model of the production process <ID1> represents the kanban wall that determines the product sequence. The model of the supermarket <ID2> contains the available inventory. Each model groups the kanban cards that the process segment currently possesses. Each kanban card is represented by a *segment requirement*. Table A.16 lists the available information for each kanban card. All kanban cards for the same product (or *material definition*) are grouped by a *production request*. The production process in figure A.21 can produce six product types (A to F). For each type, a number of kanbans is available. The amount is calculated by formula 2.2 and determines the number of storage locations for that product type in the supermarket. That number (= 13) is added as extra parameter for each production request of the *<ID2> kanban post*. The minimum batch size (= 6) is added as extra parameter for each production request of the *<ID1> kanban post*.

(b) **Detailed scheduling:** *No tasks*

(c) **Dispatching:** When a container is pulled from the supermarket (❶), then the attached kanban card is removed from the *<ID2> kanban post* and added to the kanban post (❷) of its attribute *Segment* (i.e. *<ID1>*).

(d) **Execution management:** The operator of production process *<ID1>* selects the product with the highest priority from the kanban wall (❸). That is the *production request* with the most *segment requirements* and exceeding the minimum batch size. Each produced container is associated with its kanban card and moved downstream towards the kanban post (❹) of its attribute *Location* (i.e. *<ID2>*).

(e) **Data collection:** At the production process and the supermarket, an identification system (e.g. barcode or RFID) is in place to record kanban card movements.

(f) **Tracking:** A segment response is generated for each action of a process segment. The requested segment response object defines the required structure and information. The start time, end time and other data are delivered by the data collection activity. The possible values for the activity type of the segment response are: production run (to product the container of products that is associated), waiting (in the kanban wall), inventory (in the supermarket).

(g) **Performance analyis:** Based on the historical data provided by the segment responses, the optimal number of kanban cards can be determined through equation A.11. Average daily demand ($d_{av}$) is provided by the average withdrawal rate of the product type from the supermarket. Waiting time per container ($t_w$) is the average waiting time of the kanban card in the kanban wall. Processing time per container ($t_{pc}$) is the average processing time of a container by process *<ID1>*. This recalculation can be done on a regular basis to react to changing conditions.

$$n = \frac{d_{av}.(t_w + t_{pc})s}{k} \quad \text{(A.11)}$$

with

$n$ = Number of kanban cards

$d_{av}$ = Average daily demand

$t_w$ = Waiting time per container

$t_{pc}$ = Processing time per container

$k$ = Container quantity

$s$ = Safety factor

3. **CONWIP** (Figure A.22)

   (a) **Resource management:** Each process segment gets an extra parameter to point to its *production schedule*. A CONWIP card (*segment requirement*) guides a production order (*production request*) through the value stream. The amount of WIP is limited. In figure A.22, 10 CONWIP cards (K1-K10) enforce that restriction.

   (b) **Detailed scheduling:** *No tasks*

   (c) **Dispatching:** When a production order is finished (❷), then a new production order can be released at the start of the value stream (❶). The WIP restriction is always enforced.

   (d) **Execution management:** The specific selection of production orders by processes within the value stream, can be handled in a distributed manner. For each case, a separate priority rule (e.g. FIFO, EDD, etc.) can be configured.

   (e) **Data collection:** At each production process and inventory location, an identification system (e.g. manual entry, barcode or RFID) is in place to record actions on CONWIP cards.

   (f) **Tracking:** A segment response is generated for each action of a process segment. The requested segment response object defines the required structure and information. The start time, end time and other data are delivered by the data collection activity. The possible values for the activity type of the segment response are: production run and inventory.

   (g) **Performance analyis:** Based on the historical data provided by the segment responses, the optimal value for the WIP can be recalculated. Equation A.12 shows a possible implementation based on Little's Law and determines the value for the WIP. The segment responses can give an indication for the average daily demand by calculating the card leave frequency at the end of the

| Production Schedule | Production Request | Segment Requirement | | | Material Produced Requirement | | |
|---|---|---|---|---|---|---|---|
| **ID** | **ID** | **ID** | **Material Definition** | **Segment** | **Quantity** | **Unit of Measure** | **Location** |
| **<ID1> Kanban Post** | **A Kanbans** | A01 | A | <ID1> | 10 | products | <ID2> |
| | | ... | A | <ID1> | 10 | products | <ID2> |
| | | A06 | A | <ID1> | 10 | products | <ID2> |
| | **B Kanbans** | B01 | B | <ID1> | 10 | products | <ID2> |
| | | ... | B | <ID1> | 10 | products | <ID2> |
| | | B10 | B | <ID1> | 10 | products | <ID2> |
| | **C Kanbans** | C01 | C | <ID1> | 10 | products | <ID2> |
| | | ... | C | <ID1> | 10 | products | <ID2> |
| | | C02 | C | <ID1> | 10 | products | <ID2> |
| | **D Kanbans** | D01 | D | <ID1> | 10 | products | <ID2> |
| | | ... | D | <ID1> | 10 | products | <ID2> |
| | | D12 | D | <ID1> | 10 | products | <ID2> |
| | **E Kanbans** | E01 | E | <ID1> | 10 | products | <ID2> |
| | | ... | E | <ID1> | 10 | products | <ID2> |
| | | E04 | E | <ID1> | 10 | products | <ID2> |
| | **F Kanbans** | F01 | F | <ID1> | 10 | products | <ID2> |
| | | ... | F | <ID1> | 10 | products | <ID2> |
| | | F09 | F | <ID1> | 10 | products | <ID2> |
| **<ID2> Kanban Post** | **A Kanbans** | A07 | A | <ID1> | 10 | products | <ID2> |
| | | ... | A | <ID1> | 10 | products | <ID2> |
| | | A13 | A | <ID1> | 10 | products | <ID2> |
| | **B Kanbans** | B11 | B | <ID1> | 10 | products | <ID2> |
| | | ... | B | <ID1> | 10 | products | <ID2> |
| | | B13 | B | <ID1> | 10 | products | <ID2> |
| | **C Kanbans** | C03 | C | <ID1> | 10 | products | <ID2> |
| | | ... | C | <ID1> | 10 | products | <ID2> |
| | | C13 | C | <ID1> | 10 | products | <ID2> |
| | **D Kanbans** | D13 | D | <ID1> | 10 | products | <ID2> |
| | **E Kanbans** | E05 | E | <ID1> | 10 | products | <ID2> |
| | | ... | E | <ID1> | 10 | products | <ID2> |
| | | E13 | E | <ID1> | 10 | products | <ID2> |
| | **F Kanbans** | F10 | F | <ID1> | 10 | products | <ID2> |
| | | ... | F | <ID1> | 10 | products | <ID2> |
| | | F13 | F | <ID1> | 10 | products | <ID2> |

*Table A.16: The representation of the kanban definitions of the supermarket configuration in figure A.21*

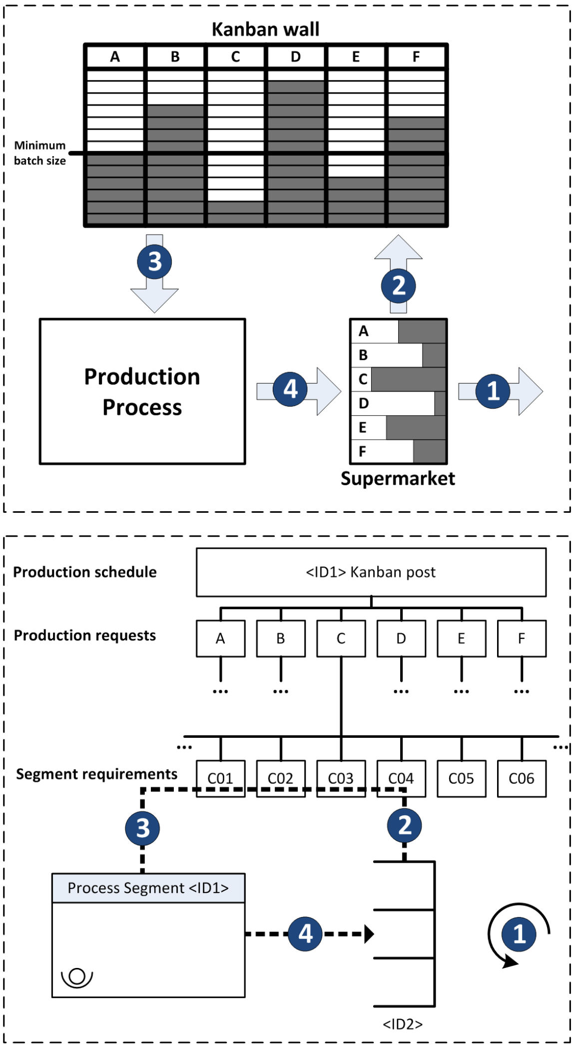



*Figure A.21: Kanban controlled supermarket configuration in ISA 95*

value stream. The lead time can be defined as the average staying time of the CONWIP cards in the value stream. The recalculation can be done on a regular basis to react to changing conditions. Reducing the WIP uncovers inefficiencies and forces an optimization of the whole value stream.

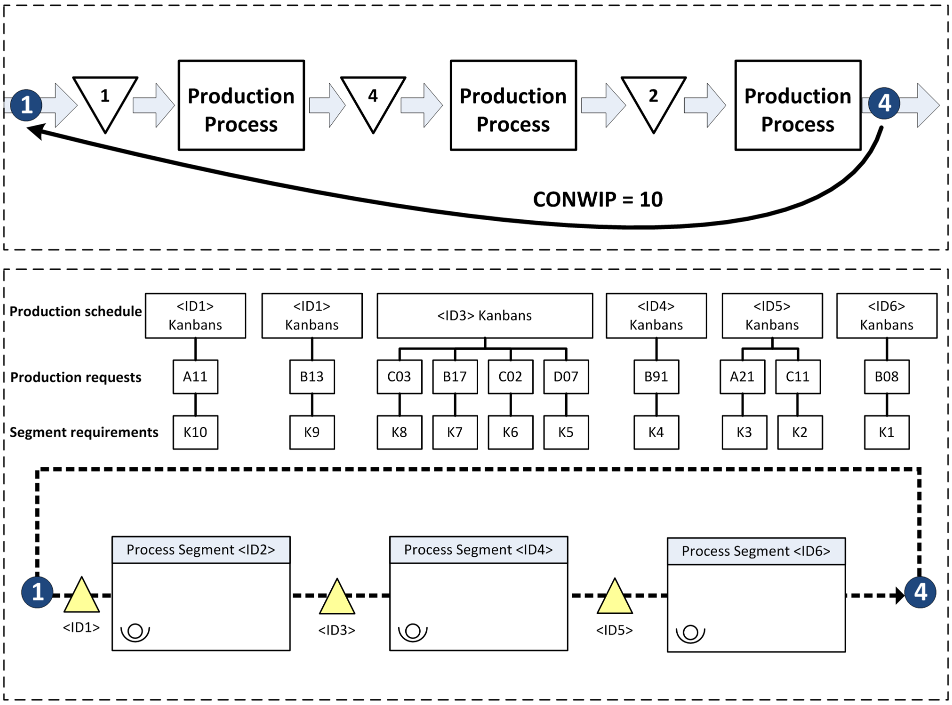



*Figure A.22: CONWIP configuration in ISA 95*

$$CONWIP = \frac{D_a . t_l}{Q} \tag{A.12}$$

with

$$\begin{aligned} D_a &= \text{Average daily demand} \\ t_l &= \text{Lead time (in days)} \\ Q &= \text{Batch size} \end{aligned}$$