International Journal of Industrial Engineering and Management (IJIEM), Vol.5 No 4, 2014, pp. 179 - 194
Available online at www.ftn.uns.ac.rs/ijiem
ISSN 2217-2661

UDK: [658.51:005.346]:005.642.4

Flow Customizer: An algorithm to Design Lean-Flow Production Systems for Mass Customization

Christos G. Chatzopoulos
Democritus University of Thrace, Dept. of Production Engineering & Management, Vas. Sophias 12, GR-67100 Xanthi, Greece, cchatzop@pme.duth.gr

Received (20.08.2014.); Revised (14.11.2014.); Accepted (23.11.2014.)

Abstract

The design of a production system in Mass Customization contexts is difficult due to product variability. This variability creates a complicated situation to engineers and Mass Customizers. This situation needs to be decoded, analysed and simplified. The present paper proposes an algorithmic procedure for designing a Lean-Flow Production System in Mass Customization contexts, named as Flow Customizer. The Flow Customizer adopts Continuous Flow Manufacturing and Demand Flow Technology approaches. They provide the fundamentals for designing demand driven continuous and mixed-model production flow. The outcome of the Flow Customizer is to create Production Modules that are connected to each other through Kanban system. The application of the algorithmic procedure is illustrated by an example that simplifies data taken from an actual context.

Key words: *Demand Flow Technology, Kanban System, Mass Customization, Production Modules*

1. INTRODUCTION

The design of production systems is a core issue studied by industrial engineering and operations management. In the last decades, technological innovations and the increase of market uncertainty put new challenges to academics and practitioners. One of these challenges is the design/redesign of production systems for companies that aim to become Mass Customizers.

The product variability that is presented in a Mass Customization (MC) context implies more efforts in the design of production systems, being able to effectively process different products. Product variability may also require frequent adjustments of the production system to maintain high performance and efficiency. In a MC environment, the set of products that has to be processed may vary frequently due to the introduction of: (a) new products, (b) new product variants and (c) quantities of both. The quantities of each product new or old may vary frequently, as well. These aspects of variability change the function of the production system.

A number of general frameworks and procedures have been developed for designing and engineering Production Systems [1][2][3][4][5][6] with particular attention to the Layout Design [7][8] and even more on specific form of cells as U or C Workcells' layout [9][10][11][12]. Unfortunately, there is lack of specific procedures for designing and redesigning Production Systems for Mass Customizers. The aim of the present work is to develop and exemplify such a procedure, borrowing some ideas from Lean and Agile production approaches, since they have been demonstrated useful for the achievement of MC [13][14]. A smoother production flow, likewise the flow in Lean Production, helps to reduce the information processing workload that is implied by customization, thus helping to achieve MC [15].

More specifically the design/redesign of a suitable production system for Mass Customizers may take advantage from the principle of one-piece-flow. The ideal production system for a Mass Customizer should be capable to process a sequence of one-piece different product variants with a level of operational performance similar to that of large batches of the same product variant. Continuous Flow Manufacturing (CFM) is a production system that focuses on "one piece flow product" at every process in assembly line [16]. CFM is associated with Just-in-time (JIT) [17] and Demand Flow Technology (DFT) [18]. "Continuous flow" describes a job's progress on the manufacturing floor where there is a minimum of job 'wait time' for a required amount of job 'process time' as the job progresses through a set of value-added operations. Thus, jobs proceed through the manufacturing process from operation to operation in a serial and continuous mode, stopping only for process time. CFM's significant benefits include: less impact from engineering changes; less work in process impact from out-of-limit inspection; less overtime resulting from operations outages; and higher productivity [19].

The developed procedure is presented step by step as an algorithm to facilitate its implementation. This algorithm is named "Flow Customizer" (please note that even though this term was previously represented to describe a system for Image Processing in 2009 [20] the present work is totally unrelated with Image Processing). The name "Flow Customizer" is intended to remind the fact that production systems' design is aimed at a continuous-smooth-fast-short and mixed-model production flow. It also conveys the idea that in order to obtain and maintain the aimed flow characteristics, production system should be tailored to meet the processes and demand requirements of new set of products. The Flow Customizer can be used to engineer and reengineer the production flow and the Production–Modules following the tenets of CFM [21] [22] in a Mass Customization context.

The Flow Customizer provides a sequence of steps that can be followed to identify Production Modules (P-Modules) and to connect them to each other through a logistics system. A P-Module is a combination of sets of tasks that build a specific set of products. Different combinations of sets of tasks create different "transformation" operations of a P-Module. A "transformation" operation consists of sets of tasks. A P-Module can consist of either one or more than one "transformation" operations. Production resources, likewise machines, robots or human beings perform these "transformation" operations. These operations are in serial mode. If the number of resources for a "transformation" operation is more than one, these resources are set in parallel and lagged mode in order to fulfill the Takt time (i.e. the pace of demand [23]). In this work, any P-Module can be any of the following production entities: an assembly line, a workcell, a single machine/operation or a warehouse/supplier.

This work includes three sections after the introduction. The first section presents the Flow Customizer algorithm. The second section exemplifies the application of the algorithm by using actual data. The concluding section presents some considerations about the applicability of the proposed algorithm and the opportunity to bring further the research that is presented in the present work.

2. THE FLOW CUSTOMIZER

2.1 **Description of the functionality**

The Flow Customizer customizes the production flow and creates Production Modules (P-Modules). P-Modules consist of sets of tasks. Different combinations of tasks to meet demand give different P-Modules. The P-Modules are Mixed-model production entities and the production system that they form is a Mixed-model system. Mixed-model production systems are considered suitable for implementing Mass Customization (MC) since they are able to efficiently process products in several variants as requested by heterogeneous markets [24] served by Mass Customizers. An appropriate combination of tasks should give a total operation time of a "transformation" operation close enough to the demand pace, namely Takt time. Takt time can be used as the basic metric for engineering and connecting the operations in a Mixed-model system [25]. An efficient production pace in Lean Manufacturing can be established by creating a value stream, where materials and operations' time "*flow*". A Kanban System can connect Mixed-model systems to each other and can establish the desired flow in the value stream [26][27].

The Flow Customizer algorithm integrates Demand Flow Technology (DFT) tools and techniques of Designing Mixed Model Manufacturing Processes [28] and Logistics Systems for demand flow processes [29]. The Flow Customizer consists of **88 Steps** and they are grouped into **7 Phases**, see below Table 1.

Table 1. Phases and Steps of Flow Customizer

Flow Customizer		
Phases	**Steps**	**Count**
1. Initialization	1-6,15	7
2. Analysis of Processes and Production Modules creation	7-14, 16-37	40
3. Production Module Balancing	38-44	7
4. Operation Balancing	45-50	6
5. Production Modules Connection	51-85	35
6. Gathering Data	86-87	2
7. Summarize results and draw Production Layout & Decoupling Points	88	1

The Phases (***Phase x***) and their Steps (**Sy**) are described below, chapter 2.2. Each Step precedes the other Step. Each successor Step is declared at the end of each predecessor Step with an arrow. Some Steps are followed by two Steps simultaneously or separately. "Simultaneously" means that the Steps can start simultaneously and "separately" means that a decision step leads to an operation or an action step, accordingly.

2.2 **The algorithm**

Phase 1, Initialization: *i = 1*, *m = 1*, *c = 1*, *j =1*, *p=1*, n=1, *s=1*, k =1 $\rightarrow$ **S1**.

S1: List all Materials M*m* & their Quantities *Qm* per Product P*p*, where *m=1,2,...,M*, and $p \in \mathrm{A}$ and $P \in \mathrm{A}$ with $p \le P$ and $\mathrm{A} = \mathbb{N}^*$ (Bill of Materials [30]). $\rightarrow$ **S2**.

S2: Define which materials are under customization as M*m,c*, where *m=1,2,...,M* and *c=1,2,...,C* & build their new BOMs, define their Quantities per Product P*p* as Qm,c_p. The pointer *i* stands for T-Module *i* or otherwise P-Module *i*, where *i = 1,2,…,I*. T-Module is defined by the Product/Process Map in **S16** that includes an analysis on specific sets of tasks ST*j*, where $j \in \mathrm{B}$ and $J \in \mathrm{B}$ with $j \le J$ and $\mathrm{B} = \mathbb{N}^*$. So, T-Module includes the sets of tasks ST*j*. Every T-Module is estimated by the function of the Flow Customizer in order to become a P-Module. This functionality is explained in ***Phase 2***. $\rightarrow$ **S3**.

S3: List all sets of tasks ST*j* and their precedencies (Bill of Processes or Operations – BOP or BOO [31]). Define the tasks of the ST*j* as SU*j*, AT*j* and M*j*. SU*j* is the Set Up task of the Actual Task AT*j* and M*j* is the distribution (Move) task of a material Mm_c or final product P*p* from task AT*j* to task AT*j+1*. List also the times *SUtj*, *ATtj* and *Mtj* for each task SU*j*, AT*j* and M*j*, respectively. So, the following is valid ST*j* = { *SUtj*, *ATtj*, *Mtj* }. $\rightarrow$ **S4**.

S4: Assign the materials into their ST*j* (from **S2** M*m,c* to **S3** ST*j*), M*m,c* $\rightarrow$ ST*j* and build the Bill of

Materials & Operations – BOMO [32]. → **S5**.

S5: Name the tasks of customized products as IP*j*, for every M*m,c* then AT*j* → IP*j*. So, the sets of tasks where customer is involved by selecting the material M*m,c* is defined as follows ST*j* = { *SUtj*, *ATtj* + *IPtj*, *Mtj* }, when a customer is involved *ATtj* = *0*, otherwise *IPtj* = *0*. → **S6**.

S6: Build Product Synchronization *i* of T-Module *i*, (define the precedence diagram of optional and feeder processes). Product Synchronization is a tool that is used in DFT [18]. → **S7**.

S15: Demand at Capacity and Takt Time definition. The following equation for Takt Time is used:

$$Takt_i = \frac{H_i \times s_i}{Dc_i} \tag{1}$$

where H_i is the actual production time of one shift of T-Module *i*, s_i the number of shifts of T-Module *i*. Takt Time is measured in minutes per one piece. It is the pace of demand. Demand at Capacity for each T-Module *i* (Dc_i) is calculated as follows:

$$Dc_i = \sum_{p \in \mathrm{A}}^{P} (Dc\mathrm{P}_p \times Qm, c_p) \tag{2}$$

*Dc*P*p* is the maximum daily production rate of P*p*. Qm,c_p is the number of M*m,c*. They are pieces of information for P*p*. Dc_i is the daily one-shift production rate that T-Module *i* should achieve every day in one shift. *Dc*P*p* can be calculated by the demand data of a past period, i.e. one year. The *Dc*P*p* is given by the following Eq. (3):

$$Dc\mathrm{P}_p = \frac{\mu_p + \sigma_p}{\text{Monthly workdays}} \tag{3}$$

where μ*p* is the mean value of the monthly sales quantity in a year of the product P*p* and σ*p* is the standard deviation. Monthly workdays is stated in 19,33 workdays per month. These can be adapted to industrial case. Materials' Demand at capacity per Day is defined as follows:

$$Dc\mathrm{M}m, c = Dc\mathrm{P}_p \times Qm, c_p \tag{4}$$

→ **S16**.

Phase 2, Analysis of Processes and Production Modules creation → **S7**.

S7: Is customization level satisfied? Are there enough options for customers? (subjective answer) Yes → **S8** or No → **S2**.

S8: Exclude feeders and optional (if there are any) of Product Synchronization *i* from next steps and keep feeders and optional until to call them and then continue with the rest, *i*=*i*+*1*. Feeders and optional are groups of tasks and are defined by the function of Product Synchronization [28][33]. → **S9**.

S9: Call tasks and build Sequence of Events (SOE) *i* (time of every task T*k,p,j* , where *k* = *1, 2, …, K*). Sequence of Events is a tool that is used in DFT [28][33]. → **S10**.

S10: Can NVA tasks be improved to VA tasks? (Lean Manufacturing & Muda). Yes → **S11** or No → **S13**.

S11: Waste minimization in operations (Lean Techniques & Tools). → **S12**.

S12: Build an Updated Sequence of events *i*, if there is one, otherwise continue. → **S13**.

S13: Are all events included? (Gemba, Go & See). Yes → **S16** or No → **S14**.

S14: Delete *i, j, k*. → **S3**.

S16: Build Product/Process Map *i*, namely the table [OPn_i , Pp_i]$_i$ for T-Module *i*, (products, operations of T-Module *i*, tasks and their times, calculations of the resources). Product/Process Map is a tool that is used in DFT [28] [33]. The table is composed by the values of Actual time of Actual Tasks At_{p,n_i} that belong to operation OP*n*, where *n* = *1,2,...,N,* that will create the product P*p* in the under-design T-Module *i*. At_{p,n_i} is calculated as follows:

$$At_{p,n_i} = \sum_{j \in \mathrm{B}}^{J} (ATt_j + IPt_j) \tag{5}$$

ATtj is the time of task *j*, *IPtj* is the time of interaction point task (Interaction Point (IP) is the task where customers customize their products by choosing among materials M*m,c*) in the operations OP*n* of T-Module *i*. The table includes the Actual time weighted and is calculated as follows:

$$Atw_{n_i} = \frac{\sum_{p \in \mathrm{A}}^{P} (At_{p,n_i} \times Dc\mathrm{P}_{p_i})}{Dc_{n_i}} \tag{6}$$

The table includes the number of weighted Resources (resources could be human operators and/or machines, robots etc.) and is calculated as follows:

$$\# RESw_{n_i} = \frac{Atw_{n_i}}{Takt_{n_i}} \tag{7}$$

where Takt time is calculated by the equation (1) and for the Product/Process Map *i* of the T-Module *i* is defined as follows:

$$Takt_{n_i} = \frac{H_{n_i} \times s_{n_i}}{Dc_{n_i}} \tag{8}$$

where Hn_i is the production or operation time of one production shift. sn_i is the number of shifts that operate the operation OP*n* of T-Module *i*. The Demand at Capacity (Dcn_i) of products P*p* that is built by operations OP*n*, is formed by the Eq. (2) into the Eq. (9). The sum of Demand at Capacity (*Dc*Pp_i) of products P*p* that are built by T-Module *i* is defined by the Eq. (10):

$$Dc_{n_i} = \sum_{p \in \mathrm{A}}^{P} (Dc\mathrm{P}_{p_i} \times Qm, c_{p,n_i}) \tag{9}$$

$$\sum_{p \in \mathrm{A}}^{P} Dc\mathrm{P}_{p_i} = Dc\mathrm{P}_{1_i} + Dc\mathrm{P}_{2_i} + ... + Dc\mathrm{P}_{p_i} \tag{10}$$

where each Dcn_i of T-Module *i* should refers to operation OP*n* only if the production time for operation OP*n* is not zero, namely stands: $At_{p,n_i} \neq 0$. The Qm,cp,n_i is the quantity of material M*m,c* that is needed in OP*n* to produce one P*p*. The $Qm,cp,n_i = 1$ if T-Module *i* produces final products. The number of Resources per product P*p* is given by the following equation:

$$\#RES_{p_i} = \frac{\sum_{n=1}^{N} At_{p,n_i}}{Takt_i} \quad (11)$$

$\rightarrow$ **S17**.

S17: Are there any product - material that its $\#RESp_i$ does not satisfy any of the following rules? $\#RESp_i$ equal to total $\#RESwn_i$? Is the following valid?

$$\#RES_{p_i} = \sum_{n=1}^{N} \#RESw_{n_i} \quad (12)$$

If yes, then the specific products P*p* or Materials M*m,c* remain to T-Module *i*. The product selection can be achieved by the following rule:

$$\sum_{n=1}^{N} \#RESw_{n_i} \times 0,7 < \#RES_{p_i} < \sum_{n=1}^{N} \#RESw_{n_i} \times 1,1 \quad (13)$$

that is used in Lean Flow Method to build product families [33]. Any relevant heuristic algorithm that can find a very good solution, by minimizing the number of selected products P*p* that are going to be extracted from T-Module *I*, is acceptable. This optimization challenge tries to satisfy Economies of Scope [34]. The goal is to achieve more products in less and more efficiently balanced P-Modules. Yes $\rightarrow$ **S18** or No $\rightarrow$ **S24**.

S18: Choose and extract products from Process Map *i*. $\rightarrow$ **S19** and **S20**. This denotes that **S19** and **S20** can start simultaneously after the completion of **S18**.

S19: Choose the remain Process Map *i* and update its Product Synchronization *i*. $\rightarrow$ **S17**.

S20: Choose the rest and Build new Product Synchronization *i=i+1* and Process Map *i=i+1*. $\rightarrow$ **S21**.

S21: Can all the products from Process Map *i* be redesigned (Design for Mass Customization - DFMC [35])? Yes $\rightarrow$ **S22**, No $\rightarrow$ **S23**.

S22: Define those products of Process Map i and check them. Use DFMC. $\rightarrow$ ***Phase 1***.

S23: Is there any product left in Process Map *i* from **S20**? Yes $\rightarrow$ **S17**, No $\rightarrow$ **S19**.

S24: Is $Takt_i$ less than max { min $\{At_{1,1_i}, At_{1,2_i}, ..., At_{1,n_i}\}$, min $\{At_{2,1_i}, At_{2,2_i}, At_{2,n_i}\}$, …, min $\{At_{p,n_i}\}$ } of OPn_i? Namely, is the following valid?

$$Takt_i < \max \left\{ \begin{array}{c} \min\{At_{1,1_i}, At_{1,2_i}, ..., At_{1,n_i}\}_1, \\ \min\{At_{2,1_i}, At_{2,2_i}, ..., At_{2,n_i}\}_2, \\ ..., \\ \min\{At_{p,n_i}, ...\}_p \end{array} \right\}_i \quad (14)$$

Yes $\rightarrow$ **S25**, No $\rightarrow$ **S26**.

S25: Add Production shifts s_i or actual production time H_i or number of Resources $\#RESp_i$. $\rightarrow$ **S15**.

S26: Group each previous work of T-Module *i*. $\rightarrow$ **S27**.

S27: Wait until all T-Module *i* reach here. $\rightarrow$ **S28**.

S28: Call Product Synchronization *i* with the fewest operations. $\rightarrow$ **S29**.

S29: Are there any optional to Product Synchronization *i* left, from **S8**? Yes $\rightarrow$ **S30** or No $\rightarrow$ **S31**.

S30: Choose upstream the first longest of the remaining optional and *i=i+1*. $\rightarrow$ **S6**.

S31: Are there any feeders to Product Synchronization *i* left, from **S8**? Yes $\rightarrow$ **S32**, No $\rightarrow$ **S33**.

S32: Choose (upstream) the first longest of the remaining feeders and *i=i+1*. $\rightarrow$ **S6**.

S33: Is there any other Product Synchronization left in **S26**? Yes $\rightarrow$ **S28**, No $\rightarrow$ **S34**.

S34: Categorize T-Module *i* into Assembly Lines, Workcells [36], Single Machines or Operations and Suppliers/Warehouses. Henceforth, name every T-Module *i* as P-Module *i*. $\rightarrow$ **S35**.

S35: Do sequential P-Modules have the same pace? Is one-piece flow in Takt time applied? Yes $\rightarrow$ **S36** or No $\rightarrow$ **S37**.

S36: Connect P-Modules directly to each other using In-process Kanban (IPK) technique & one piece-flow. IPK technique is used in TPS [37]. A Value Stream Map (VSM) can be used as a tool of displaying this connection. VSM is used in Kaizen activities for Continuous Improvement [38]. $\rightarrow$ **S38** and **S51**. This denotes that **S38** and **S51** can start simultaneously after the completion of **S36** or **S37**.

S37: Going upstream to production flow, connect the P-Modules to each other through Decoupling Points - DPs (Supermarkets). For this algorithm, a DP is a point in production stream where the pace (Takt) is different between two P-Modules. In general, DP is named the point where a customer's order penetrates in a production process [39]. Picture the step in a VSM (Kanban, IPKs, Suppliers, Warehouses). Define all DPs. $\rightarrow$ **S38** and **S51**. This denotes that **S38** and **S51** can start simultaneously after the completion of **S37** or **S36**.

Phase 3, Production Module Balancing $\rightarrow$ **S38**.

S38: Is the first P-Module an Assembly Line? Yes $\rightarrow$ **S39** or No $\rightarrow$ **S42**.

S39: Is P-Module balancing efficient in Takt time? (Is $Atwn_i = Taktn_i$?). Yes $\rightarrow$ **S45** or No $\rightarrow$ **S40**.

S40: Rearrange tasks to adjacent Operations, if it is possible, achieving a better efficiency. $\rightarrow$ **S41**.

S41: Is P-Module balancing efficient in Takt time? (Is $Atwn_i = Taktn_i$?) Yes $\rightarrow$ **S45** or No $\rightarrow$ **S42**.

S42: Add IPKs, if it is possible [28] [33]. $\rightarrow$ **S43**.

S43: Is P-Module balancing efficient in Takt time? (Is $Atwn_i = Taktn_i$?). Yes $\rightarrow$ **S45** or No $\rightarrow$ **S44**.

S44: Add resources where $Atwn_i > Taktn_i$, otherwise no any action. $\rightarrow$ **S45**.

Phase 4, Operation Balancing $\rightarrow$ **S45**.

S45: Product Complementarity for Operation balancing on time [40] and check for the Just in Sequence ability [41]. $\rightarrow$ **S46**.

S46: Are Operations efficiently balanced for mixed model in Takt time? Is the following valid?

$$Takt_i = \frac{\sum_{n=1}^{N} At_{p,n_i}}{\text{Utilized Resources}_i} \quad (15)$$

where Utilized Resources *i* is the total number of resources that is utilized in P-Module *i*. It is a managerial answer to resources' capability. Can they perform their assigned tasks in 100%, less or more? Utilized $Resources_i$ is the sum of rounded up #$RESwn_i$ of all the operations OP*n* of P-Module *i*. Yes $\rightarrow$ **S50** or No $\rightarrow$ **S47**.

S47: Use IPKs technique (add IPKs). $\rightarrow$ **S48**.

S48: Are Operations efficient balanced for mixed model in Takt time? Is the Eq. (15) in **S46** valid? Yes $\rightarrow$ **S50**, No $\rightarrow$ **S49**.

S49: Add or remove resources in operations of P-Modules, according to the following Eq. (16):

$$\frac{\left| Takt_i - \dfrac{\sum_{p\in A}^{P} At_{p_i}}{\text{Utilized Resources}_i} \right|}{Takt_i} \begin{cases} >1 \text{ , add resources} \\ <1 \text{ , remove resources, if possible} \end{cases} \quad (16)$$

$\rightarrow$ **S50**.

S50: Draw Production Layout (for P-Modules). $\rightarrow$ **S86**.

Phase 5, Production Modules Connection (Logistics) $\rightarrow$ **S51**.

S51: In VSM, going upstream, starting from the first P-Module *i* and choosing the first upstream DP*s* (*s* = *1*) of the line for designing pull sequence (or push) methods. $\rightarrow$ **S52**.

S52: Define the materials that are located in DP*s* with materials M*m,c* and M*m*, (DP*s* $\leftarrow$ M*m,c*, DP*s* $\leftarrow$ M*m*). $\rightarrow$ **S53**.

S53: Define the capable materials in DP*s* for JIT handling, (apply the 80/20 Pareto rule) [42]. $\rightarrow$ **S54**.

S54: Is the material M*m,c* approved for JIT handling in DP*s*? (Classification in X, Y and Z $\Rightarrow$ $\sigma \le \mu$, JIT handling under circumstances), where σ is the standard deviation and μ is the mean value of a material's consumption in a predefined time period [33]. Yes $\rightarrow$ **S55**, No $\rightarrow$ **S71**.

S55: Use signal techniques (Kanban) for the capable material M*m,c*. $\rightarrow$ **S56**.

S56: Is material M*m,c* of the DP*s* replenished by an Assembly Line P-Module?

$$\mathrm{Kp}m,c_i = \begin{cases} \mathrm{Kpal}m,c_i & \text{if P-Module } i \text{ is an Assembly Line} \\ \mathrm{Kpc}m,c_i & \text{if P-Module } i \text{ is a Workcell} \\ \mathrm{Kpsm}m,c_i & \text{if P-Module } i \text{ is a Sinlge Machine / Operation} \\ \mathrm{Kps}m,c_i & \text{if P-Module } i \text{ is a Supplier / Warehouse} \end{cases}$$

Yes $\rightarrow$ **S57** or No $\rightarrow$ **S58**.

S57: Name and calculate Production Kanban Kpalm,c_i of Assembly Line P-Module *i*. (Calculate Assembly Line's Ralm,c_i). The following equations are adapted to the algorithm from DFT [29] [33]:

$$\mathrm{Kpal}m,c_i = \frac{\sum_{j\in B}^{J}(SUt_j + ATt_j + IPt_j)_i}{Takt_i - \min\left\{\sum_{j\in B}^{J}(ATt_j + IPt_j)\right\}_i} \quad (17)$$

and

$$\mathrm{Ral}m,c_i = \sum_{j\in B}^{J}\left(SUt_j + ATt_j + IPt_j + \min\left\{ATt_j + IPt_j\right\}\right)_i \times (\mathrm{Kal}m,c_i - 1) \quad (18)$$

where

$$IPt_j = \begin{cases} \text{interaction point in sets of tasks } j \text{ for P}p \text{ in OP}n \text{ and } ATt_j = 0 \\ 0 \text{ and } ATt_j \neq 0 \text{ Otherwise} \end{cases}.$$

$\rightarrow$ **S63**.

S58: Is DP*s*'s material M*m,c* replenished by Workcell P-Module? Yes $\rightarrow$ **S59** or No $\rightarrow$ **S60**.

S59: Name and calculate Production Kanban Kcm,c_i of Workcell P-Module *i*. (Calculate Workcell's Rcm,c_i). The following equations are adapted to the algorithm from DFT [29] [33]:

$$\mathrm{Kc}m,c_i = \frac{\sum_{j\in B}^{J}(SUt_j + ATt_j + IPt_j)_i}{Takt_i - \min\left\{\sum_{j\in B}^{J}(ATt_j + IPt_j)\right\}_i} \quad (19)$$

and

$$\mathrm{Rc}m,c_i = \sum_{j\in B}^{J}\left(SUt_j + ATt_j + IPt_j + \min\left\{ATt_j + IPt_j\right\}\right)_i \times (\mathrm{Kc}m,c_i - 1) \quad (20)$$

where

$$IPt_j = \begin{cases} \text{interaction point in sets of tasks } j \text{ for P}p \text{ in OP}n \text{ and } ATt_j = 0 \\ 0 \text{ and } ATt_j \neq 0 \text{ Otherwise} \end{cases}.$$

$\rightarrow$ **S63**.

S60: Is DP*s*'s material M*m,c* replenished by Single Machine P-Module? Yes $\rightarrow$ **S61** or No $\rightarrow$ **S62**.

S61: Name and calculate Production Kanban Ksmm,c_i of Single Machine P-Module *i*. (Calculate Single Machine's Rsmm,c_i). The following equations are adapted to the algorithm from DFT [29] [33]:

$$\mathrm{Ksm}m,c_i = \frac{\left(SUt_j\right)_i}{Takt_i - \left(ATt_j + IPt_j\right)_i} \quad (21)$$

and

$$\mathrm{Rsm}m,c_i = SUt_{j_i} + (ATt_j + IPt_j)_i \times \mathrm{Ksm}m,c_i \quad (22)$$

where

$$IPt_j = \begin{cases} \text{interaction point in sets of tasks } j \text{ for P}p \text{ in OP}n \text{ and } ATt_j = 0 \\ 0 \text{ and } ATt_j \neq 0 \text{ Otherwise} \end{cases}.$$

$\rightarrow$ **S63**.

S62: Calculate Supplier Kanban Ksm,c_i of Supplier P-Module *i*. (Calculate Supplier's Rsm,c_i - VMI & PR). The following is valid:

$$\mathrm{Ks}m,c_i \times Takt_{n_i} = \mathrm{Ks}m,c_i \times Lt_i + Dt_i + \mathrm{Ks}m,c_i \times (1 - \text{reliability\%}_i) + \mathrm{Ks}m,c_i \times \text{SS\%} \quad (23)$$

From the Eq. (23) derives the Eq. (24):

$$\mathrm{Ks}m,c_i = \frac{Dt_i}{Takt_{n_i} - Lt_i - 1 + \text{reliability\%}_i - \text{SS\%}_i} \quad (24)$$

and

$$\mathrm{Rs}m,c_i = Dt_i + \mathrm{Ks}m,c_i \times (Lt_i + 1 - \text{reliability\%}_i + \text{SS\%}_i) \quad (25)$$

where Dt_i is the distribution time of material M*m,c* from the supplier P-Module *i*, $Taktn_i$ is the Takt time of operation OP*n* where material M*m,c* will be consumed, Lt_i is the Lead time of supplier P-Module *i* of material M*m,c*, reliability% is a possible factor that express supplier's reliability and SS% is a possible Safety Stock of material M*m,c* that is wise to be stored. $\rightarrow$ **S63**.

S63: Does Kanban Kw*m,ci* of Material M*m,c* feed an Assembly Line? The following calculations are adapted to the algorithm from DFT [29] [33]:

$$\mathrm{Kw}m,c_i = \frac{Dc\mathrm{P}_{p_i} \times Qm,c_{p_i} \times \mathrm{R}m,c_i}{H_{n_i} \times Pm,c_i} \quad (26)$$

where m,c_i refers to the material Mm,c_i that is delivered to P-Module *i* in quantities of Kwm,c_i , $Dc\mathrm{P}p_i$ and Qm,cp_i are defined in ***Phase 1***, **S15**, Rm,c_i is defined in ***Phase 5***, **S63** and also by previous steps, Hn_i is defined by previous steps and Pm,c_i is the batch or packaging size for materials that are produced or delivered by this quantity.

$$\mathrm{Kw}m,c_i = \begin{cases} \mathrm{Kwal}m,c_i & \text{if P-Module } i \text{ is an Assembly Line} \\ \mathrm{Kwc}m,c_i & \text{if P-Module } i \text{ is a Workcell} \\ \mathrm{Kwsm}m,c_i & \text{if P-Module } i \text{ is a Single Machine / Operation} \\ \mathrm{Kws}m,c_i & \text{if P-Module } i \text{ is a Supplier / Warehouse} \end{cases}$$

and

$$\mathrm{R}m,c_i = \begin{cases} \mathrm{Ral}m,c_i & \text{if P-Module } i \text{ is an Assembly Line} \\ \mathrm{Rc}m,c_i & \text{if P-Module } i \text{ is a Workcell} \\ \mathrm{Rsm}m,c_i & \text{if P-Module } i \text{ is a Single Machine / Operation} \\ \mathrm{Rs}m,c_i & \text{if P-Module } i \text{ is a Supplier / Warehouse} \end{cases}$$

Yes → **S64** or No → **S65**.

S64: Name and calculate Withdrawal Kanban Kwalm,c_i. (Use Assembly Line's Ralm,c_i). → **S72**.

S65: Do Kanbans feed a Workcell? Yes → **S66**, No → **S67**.

S66: Name and calculate Withdrawal Kanban Kcm,c_i. (Use Workcell's Rcm,c_i). → **S72**.

S67: Do Kanbans feed a Single Machine? Yes → **S68**, No → **S69**.

S68: Name and calculate Withdrawal Kanban Ksmm,c_i. (Use Single Machine's Rsmm,c_i). → **S72**.

S69: Do Kanbans feed an external Customer? Yes → **S70**, No → **S71**.

S70: Name and calculate Withdrawal Kanban Ksm,c_i. (Use Supplier's Rsm,c_i). → **S72**.

S71: For material M*m,c*, use special handling techniques, (Min/Max, Breadtruck) [43]. → **S79**.

S72: Define Kanbans' point of use for M*m,c* in P-Modules and in the DPs. → **S73**.

S73: Can two containers, at least, share the quantity of Withdrawal Kanban of M*m,c*? Yes → **S74** or No → **S75**.

S74: Connect P-Module *i* and DP*s* with One Kanban card & Dual Container. → **S76**.

S75: Share Kanban Quantity into containers using Multiple Cards, calculate their number and connect P-Module *i* and DP*s* [29] [33]:

$$N\mathrm{cards}m,c_{\,(\text{P-M})i\rightarrow\text{DP}s\rightarrow(\text{W-M})i} = \mathrm{roundup}\left(\frac{\mathrm{Kp}m,c_i}{\mathrm{Kw}m,c_i}\right)+1 \qquad (27)$$

→ **S76**.

S76: Does P-Module *i* consist of more than two Mixed Model Operations? Namely, is $N > 2$ in OP*n* ($n = 1,\ldots,N$) of P-Module *i*? Yes → **S78**, No → **S77**.

S77: Use Kanban and FIFO one-piece flow between operations for Material M*m,c*. → **S79**.

S78: Use Constant WIP Kanban (ConWIP) and FIFO one-piece flow between operations of P-Module *i* [44]. → **S79**.

S79: Is there any other material in DP*s*? Yes → **S80** or No → **S81**.

S80: Choose the next Material of DP*s*, $m = m + 1$ and $c = c + 1$ if $c \neq o$, till to choose one. → **S54**.

S81: Is there any other upstream DP*s*? Yes → **S82** or No → **S83**.

S82: Choose the next DP*s*, $s = s + 1$. → **S52**.

S83: Are all materials covered for handling? (Gemba, Go and See). Yes → **S85**, No → **S84**.

S84: Delete all and start over. (Delete *i*, *m*, *c*, *j*, *p*, *n*, *s*, *k*). → ***Phase 1***.

S85: Draw DPs Layout (for Materials). → **S86**.

Phase 6, Gathering Data → **S86**.

S86: Are all data for P-Modules and DPs gathered? Yes → **S88**, No → **S87**.

S87: Wait until all data pass through here. → **S83**.

Phase 7, Summarize results and design Production Layout & Decoupling Points → **S88**.

S88: Integrate all data and design P-Modules Layout, Decoupling Points Layout and the Kanban System.

3. APPLICATION EXAMPLE OF THE FLOW CUSTOMIZER

This section describes an application example of the Flow Customizer. The example studies a conceptual production case. The conceptual case is based on a real case, which has been simplified for presentation purpose. The considered production system produces four final products and their twenty materials. The twenty materials build the four products according to their Bill of Materials and Operations (BOMO) data, see Table 2 and Figure 1. Table 2 gives the input data of the four final products, their materials and the tasks that build them. Figure 1 gives the schematically concept of BOMO, respectively. The production technology in this example is not considered as a constraint. However, any production and technical constraint should be further examined as a possible constraint.

The gathering procedure of the initial data is described in ***Phase 1*** and its outcome is:

- BOMO, including products and their materials, quantity of the materials that build each final product, the tasks and their predecessors that build or supply the materials and build the final products, see Table 2 and Figure 1.
- Product Synchronization *1* (*i=1*) includes all ST*j*s for all the products and their materials, see Figure 2. In this Product Synchronization, the actual tasks AT*j*s are used. The actual tasks are following a serial configuration according to the arrows of the Product Synchronization. The end of each arrow is the end of the cited Actual Task. Instead of this, the total time of all tasks (SU*j*, AT*j*, M*j*) of each set of tasks ST*j* could be used. Classification of the AT*j*s into: Main Tasks, Optional Tasks to Main, Feeder Tasks to Main, Optional to Feeders and Feeders to Feeders is taken place, see Table 3. The classification is done with upstream direction of the arrows, namely the production flow.
- Demand at Capacity of each final product – Eq. (3) and their materials – Eq (4), expressed in quantities per day. The method that estimates and calculates the demand is not standard and it could be adapted to each case. In our case, Flow Customizer follows the method described in **S15** but it is not an obligatory rule. The results are displayed in Table 4 for Eq. (3) and Table 5 for Eq. (4).

The analysis of production processes of the four final products and their materials is performed in ***Phase 2***. Many different T-Modules will be created and their efficiency will be assessed, via an iterated mechanism of the ***Phase 2***, in order to find capable T-Modules to efficiently produce the products and their materials. The solution is not the best and further investigation by using heuristic algorithms could be done. The ***Phase 2*** could be upgraded into a newer version of Flow Customizer by using heuristics. Every final T-Module becomes a Production Module (P-Module) in this phase. Each final product and material is known in which P-Module will be produced. Another outcome is the number of resources with the number of their shifts that are going to be used in each "transformation" operation of each P-Module. A decision of using IPK technique or DPs is made in the last steps. This application example describes the function until the creation of T-Module 5 that will be the P-Module 5. The rest T-Modules that will be P-Modules, as well, are created by the same procedure.

P*1* is produced by the tasks AT*2* and then AT*3* (serial order), see Figure 1. P*1* consists of materials M*1*, M*9* and M*2*. M*1* is produced by the tasks AT*5* and then AT*4* (serial order). M*9* is produced by task AT*1*. M*2* is produced by task AT*6*. M*2* consists of materials M*3*, M*4* and M*4,1*. M*3* is produced by task AT*7*. M*4* is produced by task AT*8* and M*4,1* is produced by tasks AT*18* and AT*17* (serial order). The same stands for the following Bill of Materials and Operations, see Figure 1.

The procedure of ***Phase 2*** is displayed in Tables 6 to 13 and Figures 3 to 6 while its outcome is gathered in Table 14. After the steps **S7**–**S8**, Product Synchronization 2 is defined, including all the tasks of the Main Tasks Group from Table 3.

In **S9**, the SOE 2 for Product Synchronization 2 is created and further improvements for waste time elimination in **S10**–**S11** are taken place. The final SOE 2 is created in **S12**, see Table 6. After **S13**–**S14**, Product/Process Map for T-Module 2 is created in **S16,** see Table 7 and the procedure of assessment and products' extraction is done in **S17**–**S19**, see Table 8.

SOE 2, see Table 6, concludes the tasks that produce the four final products. They belong to the 1st group of Table 3. SOE 2 is used to build the Product/Process Map 2 for T-Module 2, see Table 7.

The Product/Process Map 1 includes all the four final products and their materials because it is created by the Product Synchronization 1 and is not displayed in this work for space economy reasons. By following the steps of ***Phase 2***, the product P*3* of Module *2* (with the increased bold font size) does not satisfy the rule of **S17** and is extracted from Table 7. The new version of Products/Process Map 2 after the extraction is displayed in Table 8.

T-Module *2* is restudied with the three remaining products in Table 8 after the extraction of P*3*. The three products satisfy the rule of **S17** in T-Module *2* and T-Module *2* includes the last two "transformation" operations $OP1_2$ and $OP2_2$ that produce the three products. The appropriate number of resources to cover the demand of 31 pieces of the three products is 1.11 ≈ 2 resources in $OP1_2$ and 0.99 ≈ 1 resources in $OP2_2$. The resources could be machines, humans etc., accordingly, and the number is rounded up in order to satisfy reality. This denotes three options for the $OP1_2$:

- 2 resources for the tasks in $OP1_2$ with a waste time of 89% of one shift time could be used or
- 1 resource that could be quicker for 11% more or
- More waste time elimination through Lean Production techniques implementation should be done in order to eliminate the actual time At_{p,n_i} of the three products for $OP1_2$., namely to decrease some or all of the following time 18 min. in AT*2* that is a task of the ST2, 16 min. in AT*10* that is a task of the ST*10* and 14 min. in AT*28* that is a task of the ST*28*, accordingly or
- 2 resources that could share the load of work in both the two transformation operations $OP1_2$ and $OP2_2$ of the T-Module *2*. If it is possible, the resource of the $OP2_2$ will perform the 11% of the $OP1_2$ of the other resource or
- After the creation of all the T-Modules, resources could share the load of work with other resources from other T-Modules. The T-Modules should be close enough in order to make the movement of the resources among the T-Modules more efficient. This could be a future research study for the Flow Customizer.

The same situation stands for $OP2_2$ and for all the others OPn_i. The Product Synchronization 2 is updated in **S19** by extracting the AT*20* and AT*21* that are the Actual Tasks for the P*3* and including the Actual Tasks of the other three remaining products, see Figure 3.

The **S24** gives negative answer and the procedure continuous to **S26**. All the previous work for T-Module *2*, SOE*2* and Product Synchronization *2* is grouped as study data of the T-Module *2*. The S27 is a waiting step for gathering all the data for T-Modules of the production system.

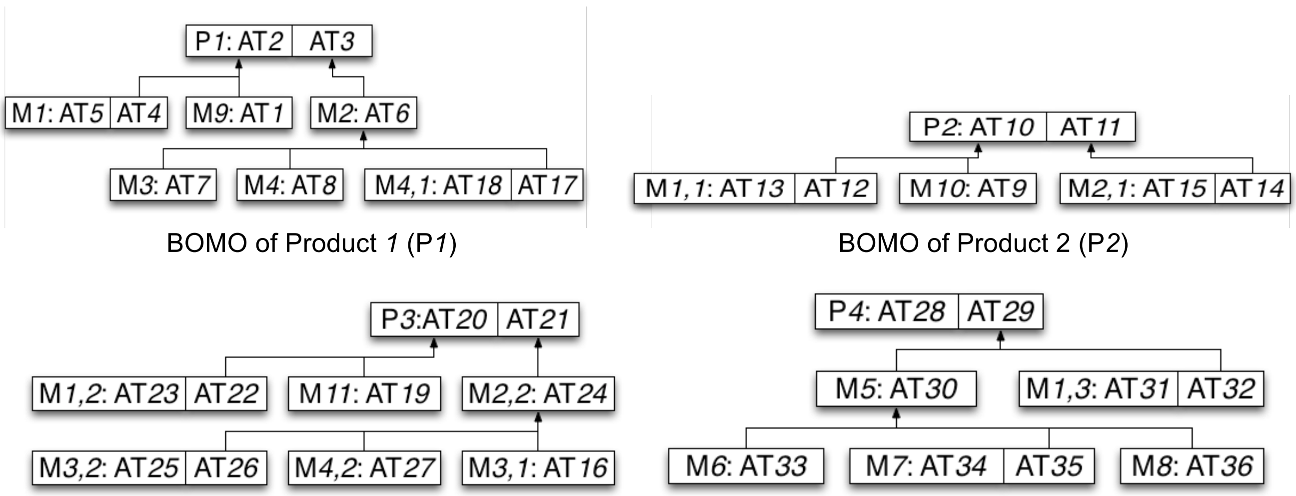
The extracted product P*3* is following the same procedure by creating a new Product Synchronization 3 with the only Actual Task AT20, a new SOE 3 and the Product/Process Map 3 for the T-Module 3 in **S20**, see Figure 4 and Table 9. SOE *3* will not be displayed for space economy reasons.

The extracted product P*3* was used as $P3_2$ for the T-Module *2* and now is used as $P3_3$ for the T-Module *3*, see Table 9. There is no any extraction here for **S17**-**S20** and the next **S21**-**S23** are not considered in our example.

The next group of tasks AT*1*, AT*9* and AT*19* in Table 3 gives the next T-Module 4 that is studied by following the same procedure as the previous modules. The Product Synchronization 4, SOE 4 and Product/Process Map 4 follow, see Figure 5, Table 10 and Table 11. The steps are the same to the previous because the function loops until all the final products and their materials are chosen and T-Modules are created.

Table 2. Bill of Materials and Operations – BOMO data

Product	Set of Tasks	BOMO level	Predecessors	*SUtj*, *ATtj*, *Mtj* (min.)	Constructs	Quantities BOM
P*p*	ST*j*		ST*j*		P*p* / M*m,c*	Qm,c_p
P1	ST1	1		40, 17, 110	M9	2
	ST2	0	ST1 , ST4	30, 18, 120		
	ST3	0	ST2 , ST6	40, 13, 10	P1	1
	ST4	1	ST5	30,40, 20	M1	1
	ST5	1		30, 100, 20		
	ST6	1	ST7 , ST8 , ST17	40, 20, 30	M2	1
	ST7	2		50, 17, 30	M3	2
	ST8	2		40, 22, 120	M4	1
	ST17	2	ST18	30, IPt17=30, 20	M4,1	1
	ST18	2		50, IPt18=30, 50		
P2	ST9	1		30, 7, 40	M10	4
	ST10	0	ST9 , ST12	20, 16, 60		
	ST11	0	ST10 , ST14	30, 14, 60	P2	1
	ST12	1	ST13	50, IPt12=70, 60	M1,1	1
	ST13	1		40, IPt13=20, 60		
	ST14	1	ST15	70, IPt14=60, 90	M2,1	1
	ST15	1		40, IPt15=20, 120		
P3	ST19	1		60, 22, 20	M11	2
	ST20	0	ST19 , ST22	50, 40, 20		
	ST21	0	ST24 , ST20	40, 70, 20	P3	1
	ST22	1	ST23	30, IPt22=40, 60	M1,2	1
	ST23	1		40, IPt23=50, 200		
	ST24	1	ST26 , ST27 , ST16	30, IPt24=90, 50	M2,2	1
	ST25	2		10, IPt25=50, 200		
	ST26	2	ST25	90, IPt26=70, 120	M3,2	2
	ST27	2		90, IPt27=12, 112	M4,2	1
	ST16	2		130, IPt16=13, 20	M3,1	1
P4	ST28	0		80, 14, 20		
	ST29	0	ST28 , ST30 , ST32	20, 17, 40	P4	1
	ST30	1	ST33 , ST35 , ST36	40, 24, 20	M5	1
	ST31	1		30, IPt31=50, 200		
	ST32	1	ST31	10, IPt32=80, 200	M1,3	1
	ST33	2		20, 16, 50	M6	1
	ST34	2		50, 20, 150		
	ST35	2	ST34	100, 50, 120	M7	1
	ST36	2	ST16	150, 19, 20	M8	2



BOMO of Product 1 (P1) BOMO of Product 2 (P2)

BOMO of Product 3 (P3) BOMO of Product 4 (P4)

Figure 1. Schematic Bill of Materials and Operations (BOMO) of the final products P1, P2, P3 and P4

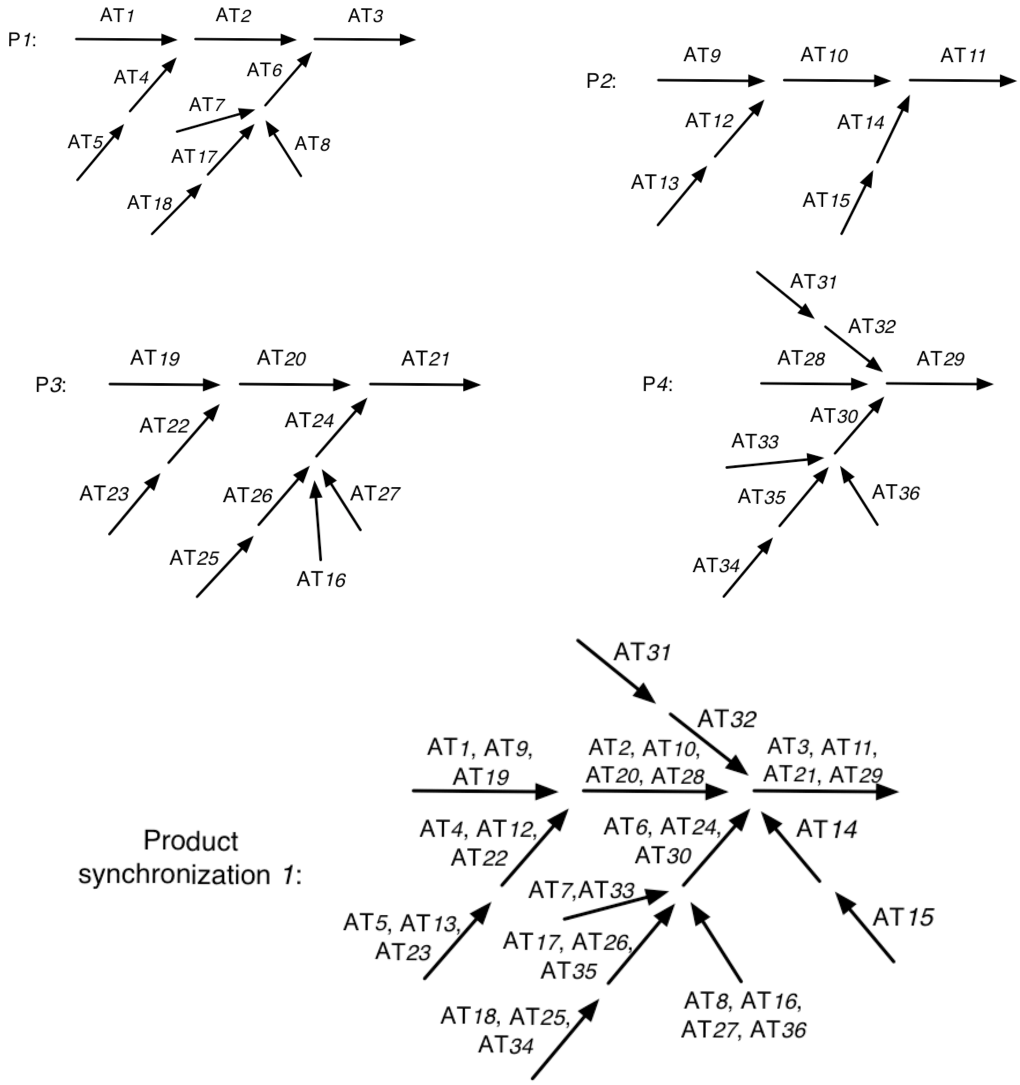


Figure 2. Product Synchronization of the final products P*1*, P*2*, P*3*, P*4* and Product Synchronization *1*

Table 3. Upstream Classification of Tasks according to Product Synchronization *1*

Classification (upstream)	Tasks Group
Main (1st T-Module under examination)	AT2-AT3 , AT10-AT11 , AT20-AT21 , AT28-AT29
Optional to Main	AT1 , AT9 , AT19
Feeders to Main	AT31-AT32
Feeders to Main	AT15-AT14
Feeders to Main	AT6 , AT24 , AT30
Optional to Feeders	AT7 , AT33
Feeders to Feeders	AT18-AT17 , AT25-AT26 , AT34-AT35
Feeders to Feeders	AT8 , AT16 , AT27 , AT36
Feeders to Main	AT5-AT4 , AT13-AT12 , AT23-AT22

Table 4. Demand at Capacity per final product

Product	Mean	Stand. Dev.	Demand at Capacity (pieces)
P*p*	**μ*p***	**σ*p***	***Dc*P*p* (roundup)**
P1	102.3	71.61	9
P2	243.6	46.28	15
P3	59.9	17.37	4
P4	95.2	39.84	7

Table 5. Demand at Capacity per final product and their materials

Product / Material	Demand at Capacity (pieces)	Quantity of each material (pieces)	Material's Demand at Capacity (pieces)
P*p*	***Dc*P*p***	***Qm,c*$_p$**	***Dc*M*m,c***
P1	9	1	9
P2	15	1	15
P3	4	1	4
P4	7	1	7
M9	9	2	18
M10	15	4	60
M11	4	2	8
M1,3	7	1	7
M2,1	15	1	15
M2	9	1	9
M2,2	4	1	4
M5	7	1	7
M3	9	2	18
M6	7	1	7
M4,1	15	1	15
M7	7	1	7
M3,2	4	2	8

M*4*	9	1	9
M*8*	7	2	14
M3,*1*	4	1	4
M4,*2*	4	1	4
M*1*,*1*	15	1	15
M*1*,*2*	4	1	4
M*1*	9	1	9

Table 6. Sequence of Events (SOE) *2* for Product Synchronization *2* and T-Module *2* before Economies of Scope

Task	VA / NVA	Set up	Actual	Move	SUM
T*k,p,j*		***SUtj* (min.)**	***ATtj* or *IPtj* (min.)**	***Mtj* (min.)**	**per Pp per ST*j***
T1,1,2	NVA	30			
T*2,1,2*	VA		18		168
T*3,1,2*	NVA			120	
T*4,1,3*	NVA	40			
T*5,1,3*	VA		13		63
T*6,1,3*	NVA			10	
T*7,2,10*	NVA	20			
T*8,2,10*	VA		16		96
T*9,2,10*	NVA			60	
T*10,2,11*	NVA	30			
T*11,2,11*	VA		14		104
T*12,2,11*	NVA			60	
T*13,3,20*	NVA	50			
T*14,3,20*	VA		40		110
T*15,3,20*	NVA			20	
T*16,3,21*	NVA	40			
T*17,3,21*	VA		70		130
T*18,3,21*	NVA			20	
T*19,4,28*	NVA	80			
T*20,4,28*	VA		14		114
T*21,4,28*	NVA			20	
T*22,4,29*	NVA	20			
T*23,4,29*	VA		17		77
T*24,4,29*	NVA			40	
SUM		310	202	350	862

Table 7. Product/Process Map *2* for T-Module *2* before Economies of Scope

T- Module 2	**OP*1*$_2$**	**OP*2*$_2$**	**Assessment**
***Pp*$_2$**	***Atp,1*$_2$**	***Atp,2*$_2$**	***#RESp*$_2$**
P*1*$_2$	*18 min. j=2*	*13 min. j=3*	2.41
P*2*$_2$	*16 min. j=10*	*14 min. j=11*	2.33
P*3*$_2$	*40 min. j=20*	*70 min. j=21*	**8.55**
P*4*$_2$	*14 min. j=28*	*17 min. j=29*	2.41
***Dcn*$_2$**	35 pcs.	35 pcs.	**Eq. (9)**
***Atwn*$_2$**	18.86 min.	20.74 min.	**Eq. (6)**
***Taktn*$_2$**	12.86 min./piece	12.86 min./piece	**Eq. (8)**
***#RESwn*$_2$**	1.47	1.56	**Eq. (7)**

Product synchronization *2* : AT*2*, AT*10*, AT*28* → AT*3*, AT*11*, AT*29* →

Figure 3. Product Synchronization *2* for T-Module *2* after Economies of Scope

Table 8. Product/Process Map *2* for T-Module *2* after Economies of Scope

T- Module 2	**OP*1*$_2$**	**OP*2*$_2$**	**Assessment**
***Pp*$_2$**	***Atp,1*$_2$**	***Atp,2*$_2$**	***#RESp*$_2$**
P*1*$_2$	*18 min. j=2*	*13 min. j=3*	2.13
P*2*$_2$	*16 min. j=10*	*14 min. j=11*	2.06
P*4*$_2$	*14 min. j=28*	*17 min. j=29*	2.13
***Dcn*$_2$**	31 pcs.	31 pcs.	**Eq. (9)**
***Atwn*$_2$**	16.13 min.	14.39 min.	**Eq. (6)**
***Taktn*$_2$**	14.51 min./piece	14.85 min./piece	**Eq. (8)**
***#RESwn*$_2$**	1.11	0.99	**Eq. (7)**

Product synchronization *3* : AT*20* → AT*21* →

Figure 4. Product Synchronization *3* for T-Module *3* before and after Economies of Scope

Table 9. Product/Process Map *3* for T-Module *3* before and after Economies of Scope

T- Module 3	**OP*1*$_3$**	**OP*2*$_3$**	**Assessment**
***Pp*$_3$**	***Atp,1*$_3$**	***Atp,2*$_3$**	***#RESp*$_3$**
P*3*$_3$	*40 min. j=20*	*70 min. j=21*	0.97
***Dcn*$_3$**	4 pcs.	4 pcs.	**Eq. (9)**
***Atwn*$_3$**	40 min.	70 min.	**Eq. (6)**
***Taktn*$_3$**	112.5 min./piece	112.5 min./piece	**Eq. (8)**
***#RESwn*$_3$**	0.36	0.62	**Eq. (7)**

Product synchronization *4* : AT*1*, AT*9*, AT*19* →

Figure 4. Product Synchronization *4* for T-Module *4* before Economies of Scope

Table 10. Sequence of Events (SOE) *4* for Product Synchronization *4* and T-Module *4* before Economies of Scope

Task	VA / NVA	Set up	Actual	Move	SUM
T*k,p,j*		***SUtj* (min.)**	***ATtj* or *IPtj* (min.)**	***Mtj* (min.)**	**per Pp per ST*j***
T*1,1,1*	NVA	40			
T*2,1,1*	VA		17		167
T*3,1,1*	NVA			110	
T*4,2,9*	NVA	30			
T*5,2,9*	VA		7		77
T*6,2,9*	NVA			40	
T*7,3,19*	NVA	60			
T*8,3,19*	VA		22		102
T*9,3,19*	NVA			20	
SUM		130	46	170	346

In Product/Process Map *4* and for the rest of our example, materials are studied and not final products. For this case the name Pp_i : M*m,c* is used to declare the material and the product that is going to be built, see Table 11. For example, the first material in T-Module *4* is M*9* and the product that constructs is P*1* in T-Module 2. This gives also the connection between the two T-Modules *2* and *4*. The M*9* is withdrawn from T-Module *4* and is consumed by T-Module *2*. This matters in ***Phase***

5. The following study shows that M*10* of P2_4 does not satisfy the rule in **S18** and it is extracted from T-Module *4*. T-Module 4 is restudied with the remaining two materials. The updated Product/Process Map *4* satisfies the rule in **S18** and Product Synchronization 4 and SOE *4* are updated. The new T-Module 4 does not satisfy the Eq. (14) in **S24** because the Eq. (8) gives $Takt1_4 = 17.3$ min. / piece that is less than max {17 , 22}, so **S25** follows. One more shift is chosen to be added for the T-Module *4*. So $s1_4 = 2$ in Eq. (8) and the Product/Process Map is updated again. Finally, all the data for T-Module *4* is gathered, see Figure 5 and Table 12.

Table 11. Product/Process Map *4* for T-Module *4* before Economies of Scope

T- Module *4*	OP1_4	Assessment
Pp_4 : Mm,c	**$At_{p,1_4}$**	**#$RESp_4$**
P1_4 : M*9*	*17 min. j=1*	3.24
P2_4 : M*10*	*7 min. j=9*	**1.33**
P3_4 : M*11*	*22 min. j=19*	4.2
Dcn_4	86 pcs.	**Eq. (9)**
$Atwn_4$	10.49 min.	**Eq. (6)**
$Taktn_4$	5.2 min./piece	**Eq. (8)**
#$RESwn_4$	2	**Eq. (7)**

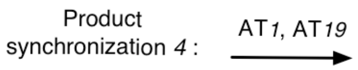


Figure 5. Product Synchronization *4* for T-Module *4* after Economies of Scope

Table 12. Product/Process Map *4* for T-Module *4* after Economies of Scope

T- Module *4*	OP1_4	Assessment
Pp_4 : Mm,c	**$At_{p,1_4}$**	**#$RESp_4$**
P1_4 : M*9*	*17 min. j=1*	0.98
P3_4 : M*11*	*22 min. j=19*	1.27
Dcn_4	26 pcs.	**Eq. (9)**
$Atwn_4$	18.54 min.	**Eq. (6)**
$Taktn_4$	34.6 min./piece	**Eq. (8)**
#$RESwn_4$	0.54	**Eq. (7)**

The procedure chooses the remaining M*10* of the P*2* and studies a new T-Module *5*. Product Synchronization *5* consists of AT*9*, see Figure 6 and the Product/Process Map *5* is displayed in Table 13. The M*10* for the new T-Module is renamed into P2_5 : M*10*. The same steps for T-Modules creation are followed, so they are presented. The results of P-Modules creation are displayed in Table 14.

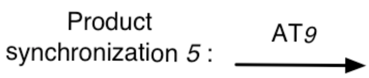


Figure 6. Product Synchronization *5* for T-Module *5* before and after Economies of Scope

Table 13. Product/Process Map *5* for T-Module *5* after Economies of Scope

T- Module *5*	OP1_5	Assessment
Pp_5 : Mm,c	**$At_{p,1_5}$**	**#$RESp_5$**
P2_5 : M*10*	*7 min. j=9*	0.93
Dcn_5	60 pcs.	**Eq. (9)**
$Atwn_5$	7 min.	**Eq. (6)**
$Taktn_5$	7.5 min./piece	**Eq. (8)**
#$RESwn_5$	0.93	**Eq. (7)**

Table 14. The final versions of the T-Modules that become Production Modules (P-Modules) of the production process

P-Module *i*	Takt$_i$ *(min./piece)*	Utilized Resources *i*	Process Technology
2	14.51	2	Assembly Line
3	112.5	1	Assembly Line
4	17.03	1	Supplier / Warehouse
5	7.5	1	Supplier / Warehouse
6	64.3	2	Single Machine / Operation
7	30	3	Single Machine / Operation
8	28.1	1	Assembly Line
9	112.5	1	Assembly Line
10	18	1	Single Machine / Operation
11	40.9	2	Workcell
12	56.3	2	Workcell
13	23.1	1	Single Machine / Operation
14	56.3	1	Single Machine / Operation
15	47.4	2	Workcell
16	50	3	Workcell
Total Utilized Resources		**24**	

The assembly line balancing problem is considered to be a traditional problem. The Flow Customizer uses three ways that are described in ***Phase 3*** with the **S38**-**S44**. Two ways are used to solve the problem and they are described in ***Phase 4*** with the **S45**-**S49**. The Utilized Resources should be flexible in order to change places among the P-Modules. The final step of ***Phase 4*** is to draw the production layout in **S50**, see Figure 8 (the outcome of this step is without the green boxes, namely the Kanban Containers. Figure 8 displays the final results of the whole algorithm and the outcome of **S50** is part of the final results.). The **S50** may be displayed as a top view of P-Modules including their “transformation” operations, their resources, the IPKs and the Decoupling Points. The boxes with an X inside are the IPKs. Each schema of the P-Module is according to the Process Technology of Table 14.
The connection among P-Modules for the materials flow is studied in ***Phase 5*** with **S51**-**S85** and it is displayed in Figure 7. Each predecessor P-Module *i* that its last OPn_i has the same Taktn_i with the first OPn_i of its successor P-Module *i*, connect to each other be using the IPK technique and can be located nearby, for example P-Module *9* and P-Module *3*, see Figures 7 and 8, for the material M*2,2* see Table 15. The rest P-Modules are

connected via Kanban Quantities. The Kanban Quantities are handling with the use of the Decoupling Points (DPs). The DPs are Supermarkets, represented by the symbol ∃ according to TPS and Lean Production.

Each DP can consist of many small or mini Supermarkets or even by one big supermarket, if the situation accepts this. Each DP is conceptually displayed by many small Supermarkets in Figures 7 and 8.

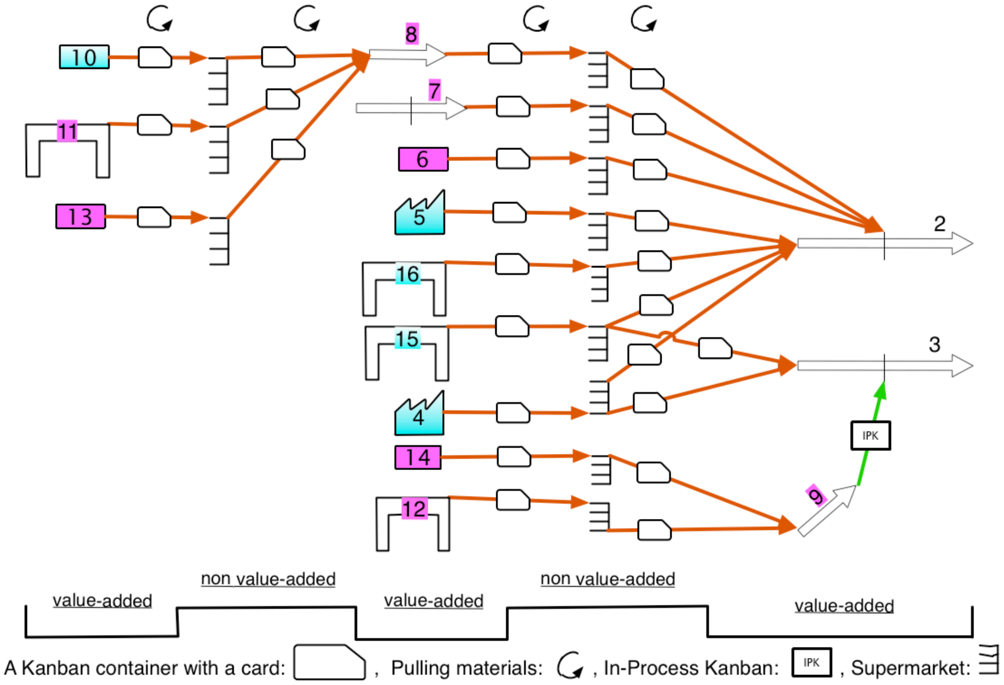


Figure 7. P-Modules and Decoupling Points Connection in a VSM

Table 15. Materials in IPK technique and their logistics data

M*m,c*	**Predecessor P-Module *i***	**DP**	**Successor P-Module *i***	**Kanban Quantity**	**Kanban Cards**
M*2,2*	*9*	IPK	*3*	1 IPK	---

The materials that are capable to be handled by JIT techniques are defined in **S53-S54**. The results from the Pareto Analysis for materials of DP*1* (choose DPs from upstream direction of production flow) are displayed in Table 16, and those of DP*2* in Table 17.

Table 16. Pareto Analysis Results per material for Decoupling Point *1*

M*m,c*	**Classification**	**Kanban System ?**
M*1,3*	Y	Approved
M*9*	Z	If σ ≤ μ, approved under preconditions
M*10*	X	Approved
M*11*	X	Approved
M*2*	Z	If σ ≤ μ, approved under preconditions
M*5*	Y	Approved
M*2,1*	X	Approved
M*3,2*	X	Approved
M*3,1*	Y	Approved
M*4,2*	X	Approved
M*1,1*	X	Approved
M*1,2*	X	Approved
M*1*	Z	If σ ≤ μ, approved under preconditions

Table 17. Pareto Analysis Results per material for Decoupling Point *2*

M*m,c*	**Classification**	**Kanban System ?**
M*3*	Z	If σ ≤ μ, approved under preconditions
M*6*	Y	Approved
M*4,1*	Z	If σ ≤ μ, approved under preconditions
M*7*	Y	Approved
M*4*	Z	If σ ≤ μ, approved under preconditions
M*8*	Y	Approved

The Approved sign in Tables 16 and 17 means that a Kanban System will be used to handle the specific material. The rest of materials will be handled by other techniques, likewise Min/Max, Breadtruck etc., in **S71**, accordingly. The Kanban Quantities calculations are described in **S56-S70**. The number of Kanban cards is calculated in **S75**. The results of the aforementioned calculations are displayed in Tables 18 and 19. There is a discrimination of using a Kanban signal or a ConWIP Kanban signal in **S76-S78**.
For comprehension reasons, the procedure of the Kanban Quantities calculation for M*1,3* is described below. From **S56** the M*1,3* is replaced by an Assembly Line, so Eq. (17) in **S57** for Production Kanban (Kp) that is Assembly Line, gives Kpal*1,3*$_6$ = *11.9* ≈ *12* pieces of M*1,3*.

$$\text{Kpal}m,c_i = \frac{\sum_{j=31}^{32}(SUt_j + ATt_j + IPt_j)_i}{Takt_i - \min\left\{\sum_{j=31}^{J=32}(ATt_j + IPt_j)\right\}_i} \Leftrightarrow$$

$$\text{Kpal}1,3_6 = \frac{((SUt_{31} + ATt_{31} + IPt_{31}) + (SUt_{32} + ATt_{32} + IPt_{32}))_6}{Takt_6 - \min\{ATt_{31} + IPt_{31} + ATt_{32} + IPt_{32}\}_6} \Leftrightarrow$$

$$\text{Kpal}1,3_6 = \frac{(30+0+50)+(10+0+80)}{64,3-50} = 11,9 \Rightarrow 12 \text{ pieces}$$

The Eq. (18) gives Ral*1,3*$_6$ = *720* minutes.

$$\text{Ral}m,c_i = \sum_{j=31}^{32}(SUt_j + ATt_j + IPt_i + \min\{ATt_j + IPt_j\})_i \times (\text{Kpal}m_{c_i} - 1) \Leftrightarrow$$

$$\text{Ral}1,3_6 = ((SUt_{31} + ATt_{31} + IPt_{31}) + (SUt_{32} + ATt_{32} + IPt_{32}))_6 + (ATt_{31} + IPt_{31})_6 \times (\text{Kpal}1,3_6 - 1) \Leftrightarrow$$

$$\text{Ral}1,3_6 = ((30+0+50)+(10+0+80))_6 + (0+50)_6 \times (10-1) = 720 \text{ minutes}$$

For the withdrawal Kanban in **S63** from Eq. (26), where $R1,3_2 = Ral1,3_6 = 720$ minutes gives $Kw1,3_2 = 11.2 \approx 12$.

$$Kwm,c_i = \frac{DcP_{p_i} \times Qm,c_i \times Rm,c_i}{H_{n_i} \times Pm,c_i} \Leftrightarrow$$

$$Kwal1,3_2 = \frac{DcP_{4_2} \times Q1,3_{4_2} \times R1,3_2}{H_{2_2} \times P1,3_2} = \frac{7 \times 1 \times 720}{450 \times 1} = 11,2 \Rightarrow 12 \text{ pieces}$$

The points in the production flow, namely the "transformation" operations of the P-Modules and the DP, where material M1,3 is built, stored and consumed is studied in **S72** and is given below: $OP2_6 \rightarrow DP1 \rightarrow OP1_2$. The number of the cards denotes also the number of the Kanban containers and if *12* pieces of M*1,3* can be contained into one container then the Dual Container with One Kanban will be used, **S74**. If the size (dimensions, etc.) of the M1,3 does not satisfy the Dual Container then Multiple cards should be calculated. The number of Kanban cards for Multiple cards, which should be used for the material M*1,3*, is calculated by Eq. (27) in **S75**.

$$Ncardsm,c_{(P\text{-}M)i \rightarrow DPs \rightarrow (W\text{-}M)i} = \text{roundup}(\frac{Kpm,c_i}{Kwm,c_i}) + 1 \Leftrightarrow$$

$$Ncards1,3_{6 \rightarrow 1 \rightarrow 2} = \text{roundup}(\frac{Kp1,3_6}{Kw1,3_6}) + 1 \Leftrightarrow$$

$$Ncards1,3_{6 \rightarrow 1 \rightarrow 2} = \text{roundup}(\frac{11,9}{11,2}) + 1 = 3 \text{ Kanban cards}$$

The 12 pieces are shared into two containers with 6 pieces capacity each and 3 Kanban cards are used. If the *6* pieces of M*1,3* cannot be contained by two containers then the number of containers should be recalculated. Otherwise the number of cards is recalculated, accordingly. For example, if the containers of material M*3,2* have a maximum capacity of *6* pieces then *36* pieces / *6* pieces = *6* containers plus *1* = *7* Kanban cards should be used. Another example for materials M*10* and M*11*, which arrive in packaging size of 10 and 5 pieces, respectively, follows. The Pm,c_i variables for materials M*10* and M*11* are $P10_5 = 10$ and $P11_4 = 5$, respectively. The number of Kanban cards is calculated accordingly. Calculation results of using a Multiple Kanban cards system is displayed below, see Tables 18 and 19.

Table 18. Materials and logistics data in Decoupling Point *1*

Mm,c	**Predecessor P-Module *i***	**DP**	**Successor P-Module *i***	**Kanban Quantity**	**Kanban Cards**
M*1,3*	*6*	*1*	*2*	12	3
M9	*4*	*1*	*2*	Min/Max	---
M*10*	*5*	*1*	*2*	909	12
M*11*	*4*	*1*	*3*	29	10
M2	*8*	*1*	*2*	Min/Max	---
M5	*8*	*1*	*2*	7	4
M2,*1*	*7*	*1*	*2*	19	3
M3,*2*	*12*	*1*	*9*	36	~~3~~ / 7
M3,*1*	*14*	*1*	*9*	2	3
M4,*2*	*14*	*1*	*9*	2	10
M*1,1*	*15*	*1*	*2*	10	2
M*1,2*	*15*	*1*	*3*	9	4
M*1*	*16*	*1*	*2*	Min/Max	---

Table 19. Materials and logistics data in Decoupling Point *2*

Mm,c	**Predecessor P-Module *i***	**DP**	**Successor P-Module *i***	**Kanban Quantity**	**Kanban Cards**
M3	*10*	2	*8*	Min/Max	---
M6	*10*	2	*8*	4	5
M4,*1*	*11*	2	*8*	Min/Max	---
M7	*11*	2	*8*	140	5
M4	*13*	2	*8*	Min/Max	---
M8	*13*	2	*8*	30	3

The final step of ***Phase 5***, namely **S85** is displayed in Figure 8.

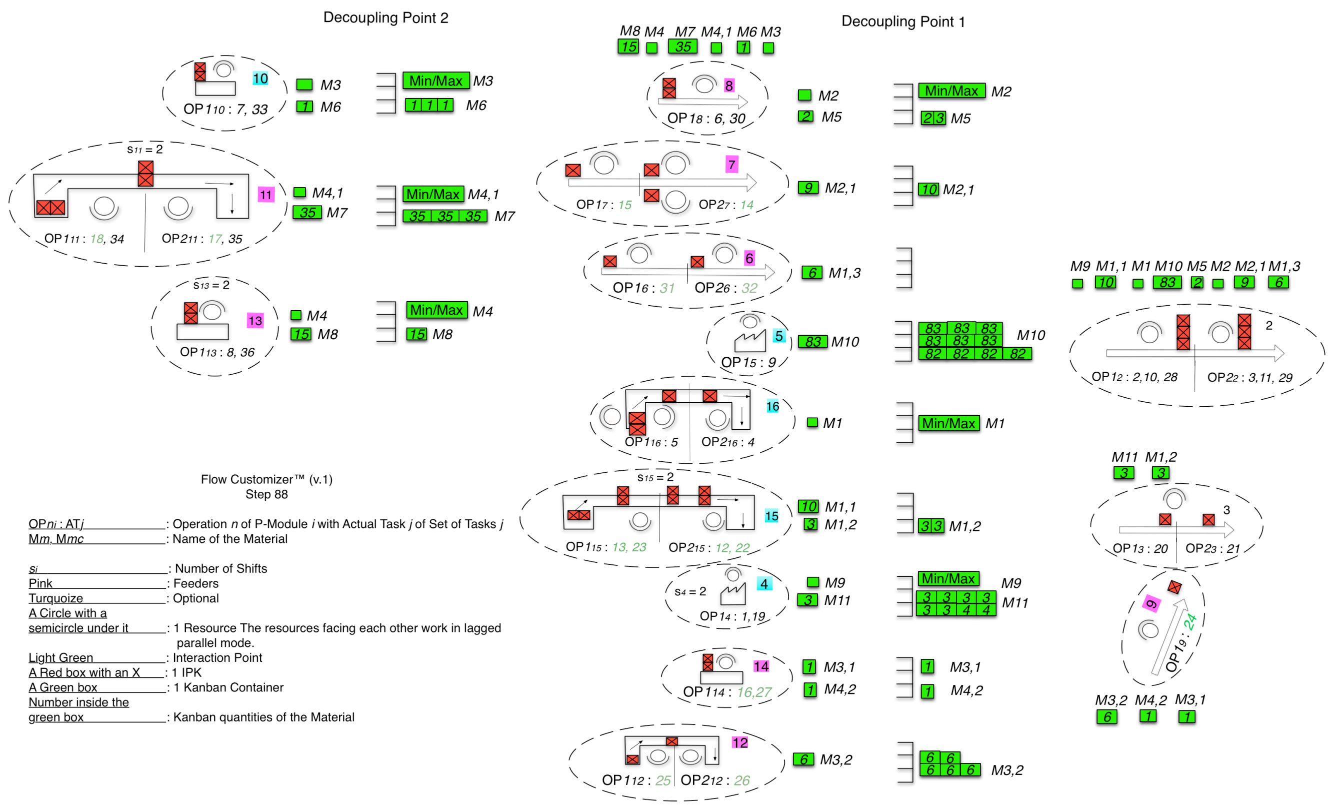


Figure 8. Top View of Production System, including P-Modules, its Operations and its Resources, Decoupling Points and Materials

The production system is customized in accordance with demand, tasks and their precedency relation, time of tasks, the products and their materials, see the initialization in ***Phase 1***. Any future demand change can be studied, by using the Flow Customizer. The aim will be to decide, if reengineering and reconfiguring the production system is efficient and how that is capable to be done.

4. CONCLUSIONS AND FUTURE RESEARCH

In the present work, an algorithm to design Lean-Flow Production Systems (L-F PS) for Mass Customization (MC) has been proposed and exemplified. The algorithm adopts Continuous Flow Manufacturing (CFM) and Demand Flow Technology (DFT) approaches. It builds different configurations of L-F PS according to demand changes, i.e. the demanded quantities of final products are dramatically changed or the set of final products is altered via launching one or more new products. P-Modules consist of operations, resources, materials and they, also, are balanced for a specific demand, following the line balancing aspects. The flow is customized in order to achieve efficiency of time, resources and materials. The algorithm allows analysing different configurations of the L-F PS, in order to be adapted to demand changes. The algorithm can be used for studying and engineering new production systems too. It will be beneficial if the process (production) technology of the P-Modules follows the idea of reconfigurable machines [45], and satisfy the principles of Reconfigurable Manufacturing Systems (RMS) [46].

The proposed algorithm provides an operative sequence of steps to design and engineer a L-F PS for a Mass Customizer, thus guiding engineers to answer to the following questions:

- Is it possible for only one P-Module to build all the ordered final products or not?
- Which final products will be built by the same P-Module and which will not?
- How many P-Modules and how many Kanban cards with their containers and their quantities will be needed to satisfy the demand in short time?
- Should the L-F PS keep or change its current configuration when a new forthcoming set of final products is launched or the demanded quantities of a previous set of final products is dramatically changed?
- Is it efficient (and to what extent) to transform a stable production system into a flexible and demand-adaptable production system?
- Would it be efficient to adapt the production system by changing production scheduling - sequencing or changing the whole configuration of the production system?

The availability of Flow Customizer pushes towards further research on Modular Production Systems for Mass Customizers. This is a valuable challenge for both practitioners and academics. The Flow Customizer idea of creating P-Modules out of sets of tasks, because of demand changes, is a new approach comparing to past works [47][48][49].

Through the steps of the algorithm, challenges and problems are addressed. The steps can be classified into classical optimization problems, such as the products extraction from a T-Module in **S17** could be transformed into a classic heuristic problem. The extraction rule in ***Phase 2*** with **S17**-**S18** is a rule of thumb rather than an accurate scientific approach.

The algorithm’s function follows an evolutionary way of studying and reengineering P-Modules and their logistics. This could lead into an automated IT tool of reengineering production systems. This IT tool could be the Flow Customizer™ (v.1). Any new updates of the algorithm’s procedure by adding new steps and phases or changing the existing steps and phases can lead into new versions of the tool.

5. REFERENCES

[1] Wu, B. (1992), *Manufacturing Systems Design and Analysis*, Chapman & Hall, London, UK.

[2] Rampersad, H. K. (1993), “*The DFA House*”, Assembly Automation*,* Vol 13, No. 4, pp. 29-36.

[3] Rampersad, H. K. (1994), *Integrated and simultaneous design for robotic assembly*, John Wiley & Sons Ltd, Chichester, England, UK.

[4] Bellgran, M. (1998), “*Systematic Design of Assembly Systems: Preconditions and Design Process Planning”*, Ph.D. dissertation, Linköping University, Sweden.

[5] Säfsten, K. (2002), “*Evaluation of Assembly Systems: An Exploratory Study of Evaluation Situations”,* Ph.D. dissertation, Linköping University, Sweden.

[6] Bellgran, M., and Säfsten, K. (2009), *Production Development: Design and Operation of Production Systems*, Springer-Verlang, London, England, UK.

[7] Hayes, R. H., and Wheelwright, S. G. (1979), “*The dynamics of process–product life cycles*”, Harvard Business Review, Vol. 57, No. 2, pp. 127-136.

[8] Hayes, R. H., and Wheelwright, S. G. (1979), “*Link manufacturing processes and product life cycles*”, Harvard Business Review, Vol. 57, No. 1, pp. 133-140.

[9] Schonberger, R. (1982), *Japanese Manufacturing Techniques: Nine Hidden Lessons in Simplicity*, Simon & Schuster Inc, New York, NY, USA.

[10] Wemmerlov, U., and Hyer, N. L. (1989), “*Cellular manufacturing in the US industry: a survey of users*”. International Journal of Production Research, Vol. 27, No. 9, pp. 1511-1530.

[11] Russell, R. S., Huang, P. Y., and Leu, Y.Y. (1991), “*A Study of Labor Allocation Strategies in Cellular Manufacturing*”, Decision Sciences, Vol. 22, No. 3, pp. 594-611.

[12] Miltenburg, J. (2001), “*U-shaped production lines: A review of theory and practice*”, International Journal of Production Economics, Vol. 70, No. 3, pp. 201-214.

[13] Tsigkas, A. C., and Chatzopoulos, C. G. (2009), “*From design to manufacturing for mass customization*”, Advances in Production Engineering & Management, Vol. 4, No. 1, pp. 19-24.

[14] Fogliatto, F. S., Da Silveira, G. J. C. and Borestein, D. (2012), “*The mass customization decade: An updated review of the literature*”. International Journal of Production Economics, Vol. 138**,** No. 1, pp. 14-25.

[15] Trentin, A., Forza, C. and Perin, E. (2011), “*Organisation design strategies for mass customisation: an information-processing-view perspective*”, International Journal of Production Research, Vol. 50, No. 14,pp. 3860-3877.

[16] Naufal A.A., Jaffar A., Noriah Y. & Halim, N. H. A. (2013), “*Implementation of Continuous Flow System in manufacturing operation*”, Applied Mechanics and Materials, Vol. 393**,** pp. 9-14.

[17] Leone, G. and Rahn, R. D. (2002), *Fundamentals of Flow Manufacturing*, Flow Publishing Inc., Boulder, CO, USA.

[18] Costanza J. R. (1990), *Quantum Leap: In Speed to Market*, JIT Institute of Technology, Denver, CO, USA.

[19] Hase, R. (1997), “*Taking Another Look at Continuous Flow Manufacturing-Continuous flow manufacturing can provide an edge in repetitive manufacturing by reducing cycle times and controlling inventories*”, IIE Solutions, Vol. 29, No. 7,pp. 30-33.

[20] Feng, L., Sun, K., Ma, G., and Nong, Y. (2009, October 30), "*Design and implementation of visual and multilevel remote sensing image processing workflow customization system*", Medical Imaging, Parallel Processing of Images, and Optimization Techniques 2009 proceedings of the MIPPR 2009 Vol. 7497 in Yichang, China.

[21] Samelson, V. R., Valle, L. N. and Wargo, J. M. (1986), "*Implementing Continuous Flow Manufacturing (CFM) at IBM East Fishkill",* National Electronic Packaging and Production Conference 1986 proceedings of the Technical Program (West and East) in Boston, MA, USA, pp. 430-438.

[22] Beal, K. (1988), "*Integrated Material Logistics and Continuous Flow Manufacturing*", International Journal of Production Research, Vol. 26, No. 3, pp. 351-373.

[23] Rother, Mike, and John Shook. (1999), *Learning to see*, Lean Enterprise Institute, Boston, MA, USA.

[24] Chatzopoulos, C. G., Tsigkas, A. C., Anisic, Z., and Freund, R. (2011), "*Making Approaches Between Flow Manufacturing and Mass Customization Industries",* Industrial Systems (IS'11) 2011 proceedings of the XV International Scientific Conference in Novi Sad, Serbia.

[25] Sianesi, A. (1998), "*An analysis of the impact of plant and management variables in a multi-stage, mixed-model production system*", International Journal of Production Economics, Vol. 56-57, No. 0, pp. 575-585.

[26] Chatzopoulos, C. G., Chatzimichailidou, M. M., and Tsigkas, A. C. (2012), "*Production Logistics for Mixed-Model Lines: Embedding Mass Customization into Demand Flow Manufacturing*", Acta Technica Corvininesis - Bulletin of Engineering, Vol. 6, No. 1, pp. 57-63.

[27] Riezebos, J. (2013), "*Shop floor planning and control in team-based work processes*", International Journal of Industrial Engineering and Management, Vol. 4**,** No. 2, pp. 51-56.

[28] Costanza, J. R. (2000), *System and method for designing a mixed-model manufacturing process*, USA Patent No. US6198980 (B1).

[29] Costanza, J. R. (2003), *Material and inventory control system for a demand flow process*, USA Patent No. US6594535 (B1).

[30] Berger, G. (1987), "*Ten Ways can MRP defeat you*", APICS 1987 proceedings of the 30th Annual International Conference, Vol. 30, pp. 240-243.

[31] Yeh, C.-H. (1995), "*Production data modeling: an integrated approach*", International Journal of Operations & Production Management, Vol. 15, No. 8, pp. 52-62.

[32] Jiao, J., Tseng, M. M., Qinhai, M., and Zou, Y. (2000), "*Generic Bill-of-Materials-and-Operations for High-Variety Production Management*", Concurrent Engineering, Vol. 8, No. 4, pp. 297-321.

[33] Tsigkas, A. C. (2012), *The Lean Enterprise: From the Mass Economy to the Economy of One,* Springer, Berlin, Heidelberg, Germany.

[34] Panzar, J. C. and Willig, R. D. (1981), "*Economies of Scope*", American Economic Review, Vol 71**,** pp. 268-72.

[35] Tseng, M. M., Jiao, J. and Merchant, M. E. (1996), "*Design for Mass Customization*", CIRP Annals - Manufacturing Technology*,* Vol. 45, No. 1, pp. 153-156.

[36] Zhang, M. and Zhou, W. (2010), "*Analyze and design a new type of production line*", Applied Mechanics and Materials, Vol. 26-28, pp. 315-319.

[37] Lu, D. J. and Kyökai, N. N. (1989), *Kanban Just-in Time at Toyota: Management Begins at the Workplace*, Productivity Press, Portland, OR, USA.

[38] Štefanić, Nedeljko, Nataša Tošanović, and Miro Hegedić. (2012), "*Kaizen workshop as an important element of continuous improvement process*" International Journal of Industrial Engineering and Management, Vol. 3, No. 2, pp. 93-98.

[39] Saghiri, S. (2007), "*Critical role of supply chain decoupling point in mass customization from its upstream and downstream information systems point of view*" in Blecke, T. and Friedrich, G. (Ed.), Mass Customization Information Systems in Business*,* IGI Global, London, England, UK.

[40] Fisher, M. L., Jain, A., and MacDuffie, J. P. (1995), "*Strategies for product variety: lessons from the auto industry*" in Bowman E. H. and Jones R. H. (Eds.), Redesigning the Firm, Oxford Univ. Press, pp. 116–154.

[41] Hüttmeir, A., De Treville, S., Van Ackere, A., Monnier, L. and Prenninger, J. (2009), "*Trading off between heijunka and just-in-sequence*", International Journal of Production Economics, Vol. 118, No. 2, pp. 501-507.

[42] Rushton, A., Oxley, J., Croucher, P. and Logistics, I. o., and Transport. (2010), *The Handbook of Logistics and Distribution Management*, Kogan Page Publishers, London, England, UK.

[43] Srinivas, T. and Narasimhan. R. (2003), "*Vendor evaluation with performance variability: a max–min approach*", European Journal of Operational Research, Vol. 146, No. 3, pp. 543-552.

[44] Spearman, M. L., Woodruff, D. L., and Hopp, W. J. (1990), "*CONWIP: a pull alternative to kanban*", The International Journal of Production Research, Vol. 28, No. 5, pp. 879-894.

[45] Koren, Y., and Kota, S. (1999), *Reconfigurable machine tool*. USA patent application 08/997,140.

[46] Koren, Y., Heisel, U., Jovane, F., Moriwaki, T., Pritschow, G., Ulsoy, G. and Van Brussel, H. (1999), "*Reconfigurable Manufacturing Systems*", CIRP Annals – Manufacturing Technology, Vol. 48, No. 2, pp. 527-540.

[47] Abreu, A. R. D. P., Beynon, H. and Ramalho, J. R. (2000), "*The Dream Factory': VW's modular production system in Resende, Brazil", Work, Employment & Society,* Vol. 14, No. 2, pp. 265-282.

[48] Berg, P., Appelbaum, E., Bailey, T. and Kalleberg, A. L. (1996), "*The performance effects of modular production in the apparel industry*", Industrial Relations: A Journal of Economy and Society, Vol 35, No. 3, pp. 356-373.

[49] Rogers, G. and Bottaci, L. (1997), "*Modular production systems: a new manufacturing paradigm*", Journal of Intelligent Manufacturing, Vol. 8, No. 2, pp. 147-156.

Flow Customizer: Algoritam za projektovanje proizvodnog sistema sa LEAN tokom za kastomizovanu industrijsku proizvodnju

Christos G. Chatzopoulos

Primljen (20.08.2014.); Recenziran (14.11.2014.); Prihvaćen (23.11.2014.)

Rezime

Projektovanje proizvodnih sistema u kontekstu strategije kastomizovane industrijske proizvodnje nije lak zadatak, jer veliki broj varijanti proizvoda usložnjava situaciju inženjerima koji treba da obezbede kastomizovane proizvode, pa je stoga potrebno ovaj fenomen "dekodirati", analizirati i pojednostaviti. U radu je predložena algoritamska procedura projektovanja proizvodnog sistema sa LEAN tokom u

kontekstu strategije kastomizovane industrijske proizvodnje pod nazivom Flow Customizer (kastomizer toka).
Flow Customizer polazi od poznatih prilaza kao što su: kontinualni tok proizvodnje i tehnologija toka upravljanog tražnjom. Oni obezbeđuju osnove projektovanja kontinualnih tokova prema zahtevima kao i mešovitih proizvodnih tokova. Primena algoritamske procedure je ilustrovana primerom koji pojednostavljuje podatke uzete iz realnog primera. U rezultatu Flow Customizer-a se dobijaju proizvodni moduli, međusobno povezani putem Kanban sistema.

Ključne reči: *tehnologija toka upravljanog tražnjom, Kanban sistem, kastomizovana industrijska proizvodnja, proizvodni moduli.*