The Role of Physical Simulation in the Re-Design of Existing Manufacturing Systems

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Abstract
Currently there are a number of computational and physical tools available to engineers/managers to model and simulate a manufacturing system. However, for a successful implementation, the manufacturing team members need to be successfully educated about the changes to their working environment and the underlying rationale for change. The Production System Design Laboratory at MIT developed a physical modeling process aimed directly at re-designing existing manufacturing systems and educating shop floor workers for the successful implementation of a new system. Creating a physical model of the material and information flow within a manufacturing system promotes visualization of a system's design and operation. It eliminates the ambiguity in defining the system design. The physical simulation provides a powerful educational and training tool that stimulates learning and improvement by all team members involved with its operation and design. This paper presents a methodology to re-design an existing manufacturing system based on implementation experience and illustrates the role and use of physical simulation in the manufacturing system re-design process.

Keywords: Manufacturing, System, Design

1 INTRODUCTION TO PHYSICAL SIMULATION IN MANUFACTURING SYSTEMS

As part of a holistic approach to creating and implementing a manufacturing system design, physical simulation is a tool that enables all stakeholders to interact with and to design a manufacturing system in a cost and time-efficient manner. Its use provides the ability for system designers to focus on how the work is done; it also enables the physical expression of a Value Stream Map (VSM)[1]. By putting the work into motion and expressing the content of a value stream map physically, the ambiguities associated with manufacturing system design and operation are all but eliminated. Once the physical simulation model of a manufacturing system's value stream is built, it may then be used for education, training and improvement activities. This paper presents a process that uses physical simulation as part of a methodology to re-design existing manufacturing systems. The process presented was born from the re-design of several value streams within a unionized automotive components plant operating in the U.S.A.

The term *physical* simulation as used herein describes the creation of a scale model of a manufacturing system's material and information flow, operational practices and standardized work activities to operate a manufacturing system. It may be used as a visualization and design tool to unambiguously define a system's design and operation. Physical simulation may be used to promote true learning. The key to promoting true learning is to first challenge the team members to understand the objectives of a manufacturing system's design and then to be able to associate the physical implementation of the system design to the achievement of the manufacturing system's objectives.

2 CREATING AND IMPLEMENTING SUCCESSFUL CHANGE WITHIN A MANUFACTURING SYSTEM.

Physical simulation may be applied to the re-design of existing manufacturing systems. Figure 1 provides a flowchart of the process for re-designing existing manufacturing systems. A manufacturing system can be defined as the following: "the arrangement and operation of machines, tools, materials, people and information to produce a value-added physical, informational or service product whose success and cost is characterized by measurable parameters [2][3]. Below is a description of the manufacturing system re-design process steps outlined in Figure 1.

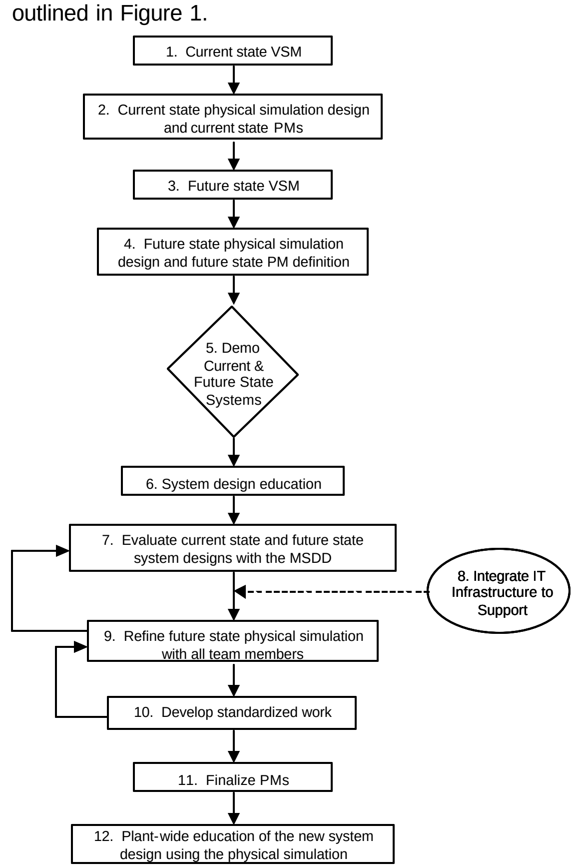

Figure 1. Flowchart of Change Process to Design and Implement a New Manufacturing System

1. Current state Value Stream Map (VSM). Establish the value stream map of the current state manufacturing system. Depict the material and information flows in the system.
2. Current state physical simulation design and current state Performance Measures (PMs). Develop a current state physical simulation based upon the existing manufacturing system's design and operating practices. The physical simulation should be a simplified, scale model of an existing value stream within a plant. This step should also capture how the existing system is measured and model the behaviour of the people within the system resulting from the existing PMs. The current state physical simulation model provides the basis for people to learn, observe and to initiate change.
3. Future state VSM. Establish the future state value stream map. The material and information flow for the future state value stream should be designed so that the objectives of a *stable* manufacturing system are achieved. [4]. A stable manufacturing system design achieves the objectives of manufacturing system stability to produce the right quantity, right mix with perfect quality to customer in spite of variation. When a problem condition occurs, the system design must indicate immediately the problem condition.
4. Future state physical simulation design and future state PM definition. Design the future state physical simulation in alignment with the future state VSM that schematically illustrates the design to achieve system stability. Concurrently, new performance measures should be established for the new manufacturing system. The performance measures should reward the achievement and improvement in the achievement of the system stability objectives of producing the right quantity, right mix with perfect quality to the customer.
5. Physical simulation demonstration of the current state versus the future state. This demonstration is the "gotcha" event. It is the learning milestone. The demonstration contrasts the operation of the current state system with focus on contrasting the role of people in a stable and an unstable manufacturing system. There is a sharp contrast in the roles of people in operating the stable versus the unstable system. In an unstable system, the people's best efforts barely keep the system alive. The focus is on trying to ship parts, sometimes any part. In contrast, the new system design enables a focused problem identification and improvement process. The people work on improving the work itself and not on merely shipping parts out the door [5]. The simulation illustrates the opportunity cost of people not working on improvement. It captures the hearts and minds of the people in the system, since they are able to see (sometimes for the first time) that their manufacturing system can be truly successful, but only if it is *designed* to achieve the objectives of a stable manufacturing system.
6. System design education. This step follows the "gotcha" milestone. Educational workshops cement the learning. During these workshops the participants learn how to design a manufacturing system to achieve the system stability objectives. The participants also learn how to design systems to achieve the objectives (FRs) and means (DPs) as decomposed by the Manufacturing System Design Decomposition (MSDD). [6]. These workshops also present case-study research results and the specifics for designing manufacturing systems [7].
7. Evaluate current state and future state system designs with the MSDD. This step ensures that the weaknesses of the existing and new system designs are identified clearly. A questionnaire has been developed to evaluate the current state and future state manufacturing system designs [8][2]. The questionnaire evaluates how well the FR-DP pairs identified by the MSDD are actually achieved by the system design. Every member of the system design team may complete the questionnaire. The MSDD is a complementary tool to VSM. The MSDD defines the objectives and means that a system design must achieve holistically. It decomposes the objectives and means within a system design to improve quality, decrease delivery response time and to improve delivery reliability. It also states the objectives and means to reduces the root causes of operational cost. The MSDD compliments VSM. VSM identifies the material and information flow necessary to achieve the objectives and means stated by the MSDD.
8. Integrate IT infrastructure to support system objectives. A benefit of constructing the physical simulation model is that the use of the supporting information technology may also be physically simulated. This step requires the live and concurrent operation of the information technology with manufacturing. The physical simulation establishes a laboratory environment in which all of the important interfaces are exposed and tested. An important aspect of this integration is to enable all participants to agree on one model for the design and operation of the manufacturing system. The participants learn how their business practices affect manufacturing and, significantly, are able to re-design their business processes to effectively meet the objectives of the manufacturing system. In fact, the participants learn that they are indeed part of the manufacturing system and learn the impact of their decisions on the design and operation of the manufacturing system.
9. Refine future state physical simulation with all team members. The simulation requires multiple iterations of refinement to ensure success. All team members are asked to run the physical simulation (concurrently with the IT support). Each team member tries to make the simulation fail and asks "what if" questions. The purpose of the step is to make the work methods in the simulation as realistic as possible and to improve the system design's robustness in addressing problem conditions.
10. Develop standardized work. Standardized work defines the work methods necessary to operate the manufacturing system. Standardized work affects the work of both salaried and hourly team members. In fact, standardized work defines how management will react to specific problem conditions. Developing standardized work is crucial to the successful launch of the new manufacturing system. The people who operate the new system must know *what* to do and *why* they are doing it. The standardized work helps to answer these questions for the operating personnel. The physical simulation enables the participants to test the standardized work methods. The standardized work methods must be written down. Significant changes to the written standardized work instructions will be made as a result of testing the standardized work methods with the physical simulation. Finalize performance measures (PMs). This step ensures that the PMs that are used to evaluate the new system's performance are

aligned with the objectives of the new system design. It can be disastrous to operate a new system design and yet measure its behaviour based on an inappropriate set of performance measures. In fact, many systems evolve into physical designs based upon the way they are measured. Plant-wide education of the new system design using the physical simulation. Once the simulation has been designed, tested and the standardized work developed, the physical simulation may be used as a powerful teaching and educational tool. This step captures the idea that everyone in the re-designed manufacturing system may be taught the new system design using the physical simulation.

3 INTRODUCTION TO DESIGNING A PULL MANUFACTURING SYSTEM

Pull is a name for a type of material and information system design [9]. Within a pull system, information flows in the reverse direction of the material, which is contrary to push systems where information and materials flow in the same direction [10].

In the presence of operational variation as evidenced by conditions such as *fall out*, in which a percentage of the parts produced are defective (for example, an assembly or a paint operation), pull is used as a *countermeasure* [11]. Pull is a physical implementation of the means, called a countermeasure, to achieve the manufacturing system stability objectives in spite of operational variation. System stability is defined as producing the right mix and right quantity of parts based on customer consumption in spite of variation (or fall out) at the individual operations (ie., paint or assembly). Pull enables customer demand information to be fed back to the upstream operations so that the system design compensates for variation at the individual operations. The system design objectives are met, in spite of problems at the individual operations.

Physically, pull is implemented through the introduction of a establishing a Standard Work In Process (SWIP) [10] inventory quantity between operations like paint and assembly. This SWIP is sometimes called a marketplace [1]. The SWIP acts to decouple the variation within operations from subsequent downstream operations. When assembly needs a part, a part is removed from the SWIP after the paint operation (assume that assembly follows paint). The goal of the paint production is to produce until its output SWIP is full. The pull and replenishment operations between paint and assembly create a type of feedback control mechanism. This mechanism is sufficiently robust to handle fallout (defective part manufacture) and other sources of variation.

The purpose of the SWIP inventory is to ensure the stability objectives of the manufacturing system are achieved in spite of the variation unique to individual operations. The greater the variation at the operation level, the greater the SWIP must be. System stability must first be established as a result of the manufacturing system design. Once stability has been achieved, the inventory (i.e, the pre-defined SWIP level) may be reduced as the sources of variation that caused the SWIP to exist in the first place are reduced.

The converse is true. The SWIP may be reduced to *expose* the sources of variation (waste) and therefore, cost, that exists within the manufacturing system [12]. True cost cannot be reduced by eliminating the piece-part contributors of cost through the indiscriminate application of cost reduction targets [5]. Improving the *work* and the *processes* that support the work in manufacturing reduces true cost.

The use of a system design to achieve system stability is a requisite first step to reducing cost. The system design can also expose waste or variation. It can provide a standardized method of problem identification and problem resolution to eliminate the variation or waste, and, therefore, true cost in the manufacturing system. Working on improving the numbers (the PMs) does not reduce cost; working on the work itself in manufacturing and improving the effectiveness of the manufacturing system in meeting its system stability objectives can only reduce cost. The key point for a successful *pull* system design is that all people in the system must have this understanding that the system design is the means to reducing total cost.

It is not enough to just show the team members and the engineers a value stream map. In a pull system, people on the shop floor should know the information and material flow for the entire value stream. As part of Prof. Cochran's methodology to re-design an existing manufacturing system in alignment with the enterprise objectives, physical simulation is one tool in the manufacturing system re-design process that can be used by all team members to visualize the design.

4 PHYSICAL SIMULATION DESIGN AND IMPLEMENTATION

The following section gives general guidance for designing and implementing a physical simulation for an actual manufacturing system.

(1) Providing detailed working instructions for each operator.

It is critical to develop detailed instructions to define the work content in the simulation. Since people participating in the simulation come from all levels within the manufacturing system (management, engineering and shop floor), most of them are not familiar with the detailed operations at the workstations; and, after the scaling and simplifying, the simulation system's appearance varies greatly from the real system. Therefore, it is needed to give clear and detailed work instructions for each participant in the simulation to ensure participants clearly understand the work content and the procedures of operation at each workstation. Clear, well-organized working instructions will enable the simulation to be carried out smoothly, especially in the case when participants are not familiar with the actual manufacturing system. This point applies to steps 2, 4, 5, 9, and 11 in the system design flowchart (Figure 1).

(2) Simulation system design.

The physical simulation should be designed to reflect the material and information flow as defined by the current and future state value stream maps. The layout of the physical simulation does not need to reflect the exact physical layout of the plant. For example, the simulation workstations can be laid out in a small line from raw material inventory, to machining, to assembly and then to pack out and shipping even though the plant is not laid out in the same physical way. The important point is that the physical simulation closely models the material and information flow relationships.

A physical simulation enables people to see the information and material flow relationships in the manufacturing system as clearly as possible. This point applies to steps 2, 4, 5, 6 and 7 of the flowchart (Figure 1).

Both time and space need to be scaled from the actual manufacturing system down to a level that enables all participants to witness all of the stages in the system. By scaling the time and distance parameters, the simulation models the physical parameters of the actual manufacturing system.

The other important issue that should be considered is the simulation of the variation within the manufacturing system. Variation is the root reason for most of the problems that occur in a manufacturing system. One of the main purposes of the physical simulation is to show people what types of variation occur within the manufacturing operations, and how this variation affects the stability of the system.

For a typical machining-assembly system, the most common variation comes from machine down time, incoming material defects and final product defects. In a real situation, these variations occur randomly and naturally; in a simulation, the system must be consistent with this randomness. The usual method used to achieve this purpose is to apply probability-generating tools, such as die or poker chips. For example, operators in a simulation can roll a die to decide whether a final assemble is defective or not.

In a physical simulation, it would be convenient to use some kind of general purpose working objects to work with, to substitute the products that are actually being produced. Lego is used for most of the simulations designed by the PSD lab. The reasons for using Lego as the working object are the following: (a) Lego of different colors and shapes can be easily used to represent different parts. Participants, who may not be familiar with the production process of the real product, are able to easily understand the assembly of Lego blocks. (b) As Lego assembly and disassembly processes are relatively standard operations, it is easy for designers to increase or decrease the complexity of the operation by adding or reducing the quantity of Lego blocks to be assembled. It is also very clear for people to see the different sub-assemblies in different workstations. (c) Lego blocks can be easily transferred in trays between different workstations in the physical simulation. (d) Lego can be easily procured and does not need any modification before being incorporated into a physical simulation.

(3) Carrying out the simulation in a manner of continuous improvement.

Even people who are familiar with the manufacturing system can get confused the first time they participate in a physical simulation. After 2 or 3 rounds, people can understand what is happening in the simulated system as the relationships between the simulated system and the actual system become more apparent. The physical simulation provides participants with clarity and an abiding respect for the objectives of the manufacturing system and its embodiment in the physical simulation. This point applies to steps 6, 7 and 11 in system design flowchart.

(4) The simulation and Manufacturing System Objectives.

The simulation becomes meaningless if participants focus on understanding the detailed operations at each individual workstation. An effective approach we at the PSD lab have found to encourage people to think systematically is to use objectives to orient the simulation. This is in accordance with the system design steps 7 and 11. At the beginning of each round of simulation, several important system objectives are announced, such as meeting customers' demands at the right time, in the right mix and with perfect quality. After each round, questions according to these objectives are asked, such as "Did we meet the customers' needs?" "What kinds of variation prevented us from achieving the manufacturing system objectives? Such questions can greatly help to focus peoples' attention on the system design. By answering these objectives-oriented questions, people can contrast the current state and future state system designs.

5 APPLICATION OF PHYSICAL SIMULATION IN AUTOMOTIVE PARTS MANUFACTURING PLANT

The following section describes a physical simulation design/implementation carried out by PSD lab in an automobile part plant. One of the major products of this plant is a plastic bumper for different types of cars. The plant intends to implement a pull production system in their existing bumper production system by using Kanban to control information flow. PSD lab designed the new system according to the MSDD framework [2]. However, in order to implement the new design successfully, it is essential that all stakeholders involved with bumper production have a detailed knowledge of the production system and its dynamics. In other words, they need to see the value streams of the incoming pull system. Under this situation, a physical simulation was designed and carried out in the plant, all participants had the opportunity to take part in the simulation and the physical simulation greatly helped the understanding and implementation of the new system. The simulation was a deemed a success for this reason.

5.1 Introduction of basic production processed of bumper production area.

The basic processes of bumper production include injection molding, painting, assembly and pack out. Plastic bumpers are first formulated by injection molding plastic pellets into parts. An AS/RS transfer the injection-molded bumpers to storage. It then sends different types of bumpers to the painting booth. After being painted, the bumpers are sent back to the AS/RS again by AGVs. The assembly area's production schedule then requests the AS/RS to send bumpers of a particular type and color to the assembly area, where finally assembly and pack out for customers occurs. Figure 2 gives provides a layout diagram of the bumper production area.

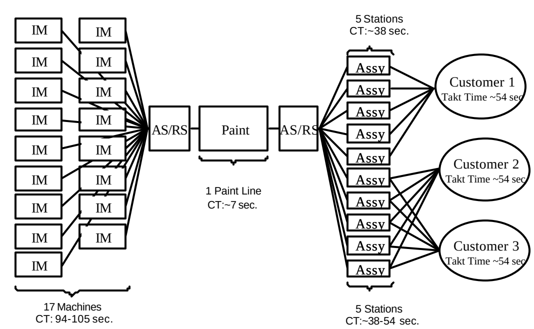

Figure 2: Diagram for physical layout of bumper production area

5.2 System design – current state and future state

The current production approach of the bumper area is characterized as "push" system. All working processes, including injection molding, painting, assembly, as well as AS/RS, are controlled by an MRP based production control system. Figure 3 shows the VSM of the initial, current-state system design.

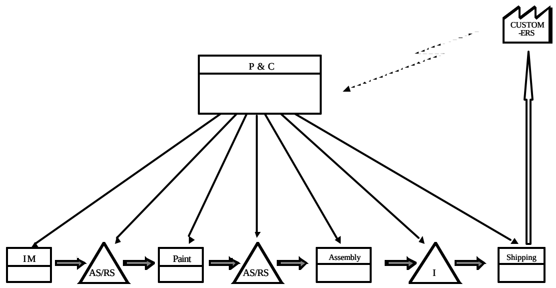

Figure 3: Current state value stream map

The current system's major problem is its inability to produce the right quantity and right mix of products according to customer demand. As the production is unstable and unpredictable, does not operate according to a balanced operating pattern and is controlled by demand forecast rather than by actual customer need, considerable inventory needs to be stored in the AS/RS to absorb these instabilities. As more and more customers of this plant change from large-run size batch-production to short run sizes as evidenced by In-line-vehicle-sequence (ILVS) production, the variation in the types and colors of bumpers has increased dramatically. The push system was unable to meet most of the demands from the customer on time. It was necessary to change from a "push" to a "pull" system as a countermeasure to accommodate the instability of the individual operations and to provide a basis for improvement and long-term cost reduction.

Figure 4 shows the future state pull system of the bumper production value stream. Customers' needs pull production via a production-leveling schedule. From the value stream it can be seen that the information flow starts from assembly, then travels back to painting, and finally to injection molding, through the kanban circulation system.

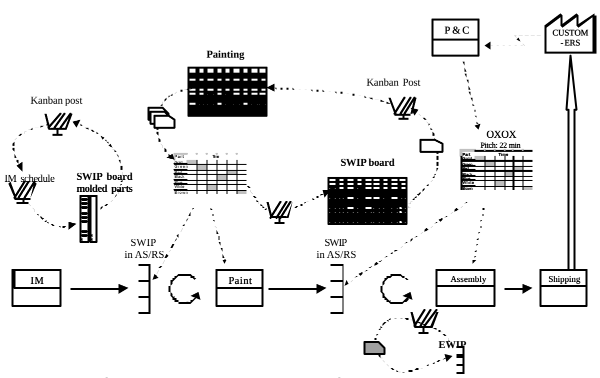

Figure 4: Future state value stream map

5.3 Physical simulation design

Parameter scaling for simulation

There are no preset rules for the simulation parameter scaling calculation. It is very case specific and should be decided according to the actual system to be simulated. Usually it is desired to finish one round of simulation in less than 15 mins, and this time period often stands for 1 shift (8 hours). After setting the simulation time, the designers of the simulation can decide the workload (how many parts to be built in this time period) and time allocation for each operation, according to the actual situation.

Simulation layout

The simulation layout does not need to be an actual replication of the factory floor. Instead, simulation workstations should be structured according to the value stream flow. The simulation designers set the time allocation of each operation.

Establish work instructions for operators in simulation.

Since not all people in the simulation are familiar with the operation details, it is very important to establish a clear and detailed standardized work instruction for every operator. The following is a typical standardized work instruction sheet for the painting operator. These instructions are revised, as the simulation is refined.

Work Instructions - Paint

- The cycle time in for the paint operation is 81 seconds
- Take 6 racks with molded parts and dump them into the large green box
- Determine the status of the painted parts according to the die scheme by rolling the dice
  - Put buff parts into buff bin
  - Put repair parts into repair bin
  - Put good parts into good bin
- Minimize number of partial bins
- Write down number of defects on "defect sheet"
- Bring good parts into AS/RS
- Bring buff parts and repair parts into rework area
- Take a break of 1.3 minutes during every shift

Number	Status
1	1x buff
2	1x repair
3	1x repair
4	good
5	good
6	good
6+6	all scrap

Fig 5: Example of a work instruction

5.4 Carry out the simulation

In carrying out the simulation, the simulation designers should be act as "supervisors," to observe the entire simulated system and to make sure all operators are following the working instructions. The simulation designers should be ready to answer any question that the participants may have.

After each round, the supervisor should make a concise summary and discuss with participants the simulated results. The discussion should focus on the problems that occurred in the simulation process, and should trigger suggestions for future improvement. Fig 6 shows a photo of a physical simulation carried out at an automotive parts manufacturing plant as part of the manufacturing system re-design process.

Fig 6: A physical simulation carried out at automotive manufacturing plant in the U.S.A.

6 SUMMARY

By scaling production parameters and substituting the real machines and working objects with people and Legos, physical simulation enables people to carry out "production simulation" in a relatively small space. Its main objective is to teach people to see the value streams of the whole system, and establish a systematic methodology to improve and redesign the existing manufacturing systems. The PSD lab of MIT designed several physical simulations for cooperating plants to help re-design their existing manufacturing systems and implement a new manufacturing system. The success of these physical simulations shows that it is a powerful tool in manufacturing system re-design and implementation.

7 ACKNOWLEDGEMENT

Although the physical simulation has appeared in many manufacturing companies and research institutes for a number of years, few of them have described academic research on the methodology for designing and implementing this valuable tool.

This paper is based on the pioneering work of the PSD lab of MIT. For the first time, an academic level study of incorporating physical simulation into the process of production system design was established. We want to thank Joachim Linck, Patrick Neise, and Jey Won for their valuable work, which contributes to the formation of this paper.

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