DECISION SUPPORT FOR MANUFACTURING SYSTEM DESIGN – COMBINING A DECOMPOSITION METHODOLOGY WITH PROCEDURAL MANUFACTURING SYSTEM DESIGN

Prof. David S. Cochran
dcochran@mit.edu
Massachusetts Institute of Technology
Cambridge, MA 02141, USA

Joachim Linck
linck@mit.edu
Massachusetts Institute of Technology
Cambridge, MA 02141, USA

Prof. G. Reinhart
gunter.reinhart@iwb.tum.de
Technische Universitaet Muenchen
85747 Garching, Germany

Michael Mauderer
michael.mauderer@iwb.tum.de
Technische Universitaet Muenchen
85747 Garching, Germany

ABSTRACT

A methodology is developed, which combines a top-down design procedure for manufacturing systems with a decomposition of manufacturing system requirements. Traditional design procedures for manufacturing system design guide the design process from the analysis of the product to be produced through detailed design of the system to operational execution planning. While such design procedures provide the designer with a structured top-down approach, it does not enable the designer to recognize how design decisions at various stages affect the overall system requirements.

The decomposition of manufacturing system requirements applies axiomatic design. It relates system objectives to design solutions and enables the connection of design decisions such as equipment selection and operator work loop design with higher-level system objectives such as improvement of quality, reduction of throughput time, and cost control. However, the decomposition does not provide the designer with a procedure for the physical system design.

The paper elaborates how the traditional design procedure can be linked with the decomposition of manufacturing system requirements. The combination of the design procedure with the functional decomposition provides designers with a better tool to efficiently design manufacturing systems by considering manufacturing system requirements throughout the design process. A case study illustrates how the integrated design framework can be applied.

Keywords: manufacturing system design, manufacturing system decomposition, axiomatic design, design procedure

1 INTRODUCTION

Companies are forced to improve the effectiveness and efficiency of their manufacturing systems to deliver a higher variety of products with shorter life cycles in a shorter period of time. Many companies have tried to implement concepts such as agile manufacturing, lean manufacturing and so forth. While many companies have succeeded in doing so [Liker, 1998], numerous companies have failed. Often companies implement pieces of an overall system such as a Kanban system or implementing U-form manufacturing cells without relating those design decisions to system objectives.

Traditional design procedures for manufacturing system design guide the design process from the analysis of the product to be produced through detailed design of the system to operational execution planning. While such design procedures provide the designer with a structured top-down approach, it does not enable the designer to recognize how design decisions at various stages affect the overall system requirements. Furthermore, the design procedure does not show how low-level design decisions affect high-level system objectives. The key to an effective system design is to define the relationship of the implementation to achieving the objectives. System design methods are not effective when: (1) only the objectives of a system are thought about in the absence of a solution, (2) when solutions are developed without tying them to the objectives of a system, (3) when only piece parts of a system design are implemented without understanding the overall objectives.

The manufacturing system design decomposition (MSDD) states the objectives (functional requirements) of manufacturing system design and relates them to design solutions (design parameters) by applying axiomatic design [Cochran, 1999]. The MSDD states the functional requirements (FRs) of a manufacturing system design. The FRs are independent of the specific physical entities such as manufacturing stations or cells. The stated FRs have to be considered in all areas of the manufacturing system. The goal of the MSDD is to structure the stated FRs and to achieve independence through the selection of design parameters (DPs). The process of decomposition relates low-level design decision to high-level system objectives, and to show design sequences i.e. highlight which decisions have to be made first. The MSDD does not guide a designer to a complete specification of a physical entity. The MSDD rather supports a designer to understand the critical relationships between a FR and the physical or logical

solution (DP). Thus, the MSDD is not a manufacturing system design approach in itself, but more a decision support tool, which should be used along with a physical design method.

This paper discusses how both the traditional design procedure and the MSDD can be combined to create a manufacturing system design methodology. The combination allows to benefit from the advantages that capture both approaches.

2 LITERATURE REVIEW AND MOTIVATION

Manufacturing system design is becoming an ever more intensive area of research [Wildemann, 1998, Hopp, Spearman, 1996]. There is a high pressure in industry to streamline the manufacturing operations. The publication of The machine that changed the world [Jones, Womack, 1990] stimulated major redesign efforts in manufacturing companies throughout the 1990's [Liker, 1998]. The need for manufacturing system design methodologies became evident as numerous companies struggled with the implementation of well understood concepts such as Kanban and cellular manufacturing [Maccoby, 1997].

There have been numerous manufacturing system design concepts developed in literature over the last decades [see e.g. Askin, 1993, Wu, 1992, Warnecke, 1993, Hopp, Spearman, 1996]. Manufacturing systems are hierarchical in nature [Askin, 1993, p.8]. The majority of the manufacturing system design methods develop a physical hierarchy e.g. plant level, department level, station level [Wu, 1992, pp. 301]. Many German and European system design procedures follow a top-down approach in designing a system (see section 3) [e.g. Kettner, 1984, Warnecke, 1993]. While these design methods provide a guidance for the physical design, the shortcoming is a lack in providing a link to the objectives that must be achieved by manufacturing systems.

Wildemann emphasizes the concept of segmentation by creating factories within the factory [Wildemann, 1998]. While this method develops a physical hierarchy of the manufacturing system, it does not word explicitly the objectives, which are to be achieved by the design.

Monden provides a detailed analysis of the Toyota production system (TPS) [Monden, 1998]. He develops a functional hierarchy, which highlights how different concepts of the TPS build on each other to ultimately achieve cost effective production [Monden, 1998, p.4]. The main difference to the previously described approaches is that his hierarchy is not related to physical entities but to functions such as quality control, throughput time, flexible workforce. Shingo describes the mechanisms of the TPS [Shingo, 1989] without providing a framework showing the dependencies.

The Manufacturing System Design Decomposition (MSDD) aims to provide a means to clearly state the objectives of manufacturing systems from the functional point of view [Cochran, 1999].

The goal of this paper is to integrate a physical design procedure with a functional decomposition. The paper concentrates on discrete manufacturing. The proposed manufacturing system design methodology should be applicable to different system configurations such as job shop environment or flow manufacturing.

The paper first discusses a typical procedural method for manufacturing system design (section 3). Section 4 then discusses the MSDD. We then discuss the different approaches (section 5) before developing their combination (section 6). Section 7 provides an application of the proposed integrated framework.

3 DESCRIPTION OF PROCEDURAL APPROACHES FOR MANUFACTURING SYSTEM DESIGN

Many production system Design approaches provide a top-down procedure for system design. This section briefly discusses a systematic system design procedure according to [Kettner, 1984]. The planning procedure consists of phases such as rough planning, detailed planning etc. and are similar among the different authors. The phases are partially overlapping and require an iterative procedure. The different phases according to e.g. Kettner are as follows:
- determination of system objectives
- preparation
- rough planning
    - ideal planning
    - realistic planning
- detailed planning
- operational planning
- execution.

The objectives of the "goal determination phase" include time framing and cost planning, and the relation to corporate objectives. The second phase evaluates the as-is situation of the company, performs a market analysis, and defines the product spectrum. Furthermore, the phase includes the determination of production technologies, demand planning, and a more detailed goal determination using measures e.g. for needed floor space per machine. Material requirements are estimated to roughly plan the sizes of buffers and inventories.

This information forms the basic input for the rough planning. Rough planning consists of two steps: the ideal planning and the realistic planning. The ideal planning elaborates an ideal functional scheme including optimal relationships of system elements, forming of physical zones and departments, design of the organization, and operational procedures. The realistic planning uses this information and considers existing restrictions such as land properties and buildings. The output of the realistic planning is a determination of required space, a functional scheme to scale, and several alternatives for the layout and an evaluation of the developed alternatives.

The detailed planning phase examines the elaborated layouts, and further extends them into more detail. This includes the selection of equipment, material flow analysis, optimization of layout configurations, space requirements calculations, planning of material supply, station design, and detailed layout of the production areas. The last two phases are mainly concerned with

the elaboration of a realization plan, consideration of changes and their implementation.

This paper primarily addresses the phases preparation, ideal planning, realistic planning, detailed planning, and execution.

4 MANUFACTURING SYSTEM DESIGN DECOMPOSITION (MSDD)

The manufacturing system design decomposition (MSDD) is a general functional decomposition of the shop floor design and operation [Cochran, 1999]. The decomposition relates system design objectives (functional requirements or FRs) to design solutions (design parameters or DPs) by applying axiomatic design. The general structure of the MSDD is shown in Figure 1.
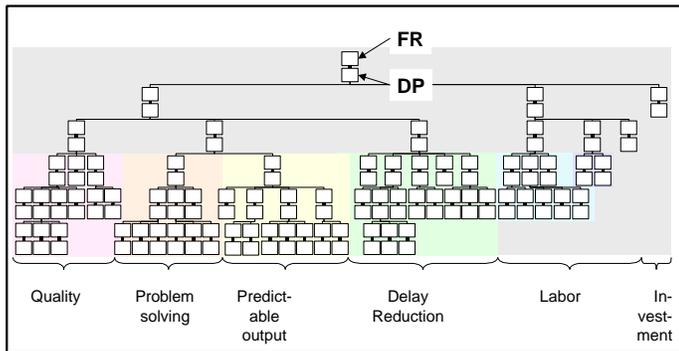
Figure 1. General structure of the MSDD [Cochran, 1999]

Each pair of boxes represents a FR->DP pair. The decomposition eventually leads to six different functional areas: quality of the manufacturing output, problem solving for existing disruptions, achieving predictable time output from the system, reducing mean throughput time, direct and indirect labor, and investment.

The following paragraphs briefly describe the structure of the MSDD. A detailed description can be found at [Cochran, 1999]. Axiomatic design requires the following steps during the design procedure: 1. state the FRs, 2. state the DPs, 3. state the dependencies between DPs and FRs, 4. decompose the DPs if necessary. The top three levels of the MSDD are shown in Figure 2 and illustrate how axiomatic design is applied.
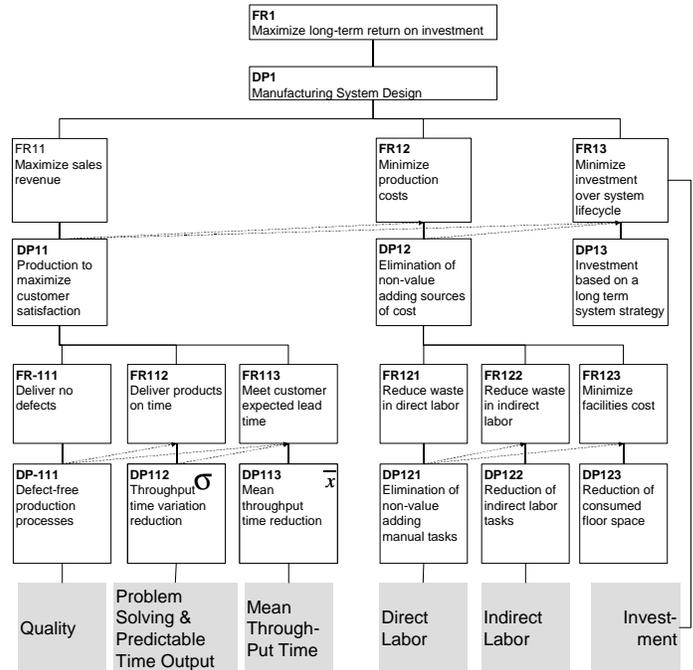
Figure 2. Top three of six levels of the MSDD. The arrows between DPs and FRs indicate the dependencies between DPs and FRs.

The decomposition starts from the viewpoint of the shareholder. The requirements of the internal and external customers of the manufacturing system are considered during the decomposition. The shareholder wants to maximize the return on investment. Thus, the top level FR might be stated as follows:

FR1 = Maximize return on investment (ROI).

The chosen DP is to design a manufacturing system. Therefore the DP becomes:

DP1 = Manufacturing system design

The emphasis on DP1 is on 'design', expressing that a system should be designed rather than evolve. The next step in the design process is to decompose the manufacturing system design and to define the FRs of the next level. The formula that calculates the ROI derives the FRs for the next level of decomposition:

$$ROI = \frac{\text{Sales - Cost}}{\text{Investment}} \quad (1)$$

The parameters in the ROI equation define three FRs for the next level:

FR11 = Maximize sales revenue
FR12 = Minimize production costs
FR13 = Minimize investment over system lifecycle.

To increase sales revenue, the production must satisfy the requirements of the customers. Minimization of costs leads to targeting cost. The investment in a manufacturing system considers the overall system to ensure overall compatibility of the equipment. The corresponding DPs are therefore:

DP11 = Production to maximize customer satisfaction
DP12 = Elimination of non-value adding sources of cost
DP13 = Investment based on long term system strategy

The arrows in Figure 2 indicate the dependencies of the design. DP11 affects all FRs of the second level. If the customer is

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unsatisfied with the outcome of the production and will not buy the product, unnecessary labor costs are incurred and unnecessary investment has been made. If there are non-value adding sources of cost additional investment may be required to achieve e.g. a desired capacity level.

The clear statement of the dependencies guides the order of decision making in the design of the manufacturing system. The design decisions, which influence most design objectives, must be made first [Suh, 1990, p. 101]. This statement means that DP11 has to be satisfied first, before going to DP12 and DP13. The MSDD reflects the sequence of decision making by arranging the DPs from left to right, depending on how many FRs the DPs affect.

Further decomposition of the DPs leads to the six distinguished areas shown in Figure 1. Each area is further decomposed – particularly the four left ones. The decomposition incorporated design and operational aspects such as DP-T12 "Design quick changeover for material handling and equipment" and DP-P141 "Standard work in process between subsystems."

4.1 DISCUSSION OF MSDD

The MSDD has the following characteristics and benefits:
- Focus on shop floor design.
Aspects such as product design or marketing are not considered.
- Clear statement of system objectives and design solutions.
Ultimately the system objectives must be satisfied. There may be several ways to achieve them i.e. different DPs, but the objective does not change. Many tools of "lean" production are design parameters and their implementation without knowing the underlying objective is likely to lead to failure, e.g. the configuration of a U-shaped manufacturing cells supports the achievement of several objectives (effective operator movements, small transportation distances, fast reaction to production disruptions etc.). However, implementing a U-shaped cell with operators bound to their work station and producing in large batches at each station will not achieve the intended objectives. The MSDD shows how particular design solutions affect the overall system objectives and relates low-level decisions to high-level objectives.
- Functional not physical decomposition.
The MSDD does not reflect a physical arrangement of systems (e.g. a manufacturing cell or a job shop environment). It states general objectives of manufacturing systems. Special configurations would require too detailed decomposition and would make the MSDD not general applicable.
- Distinction of six major areas of design.
The six areas evolved from the decomposition process: quality, problem solving, predictable output, delay reduction, labor, investment (Figure 1). They enable the designer to refer to common functional aspects during the design process. Similar categories are often found in frameworks for manufacturing strategy [Miltenburg, 1995].
- Integration of design and operational aspects of manufacturing systems.
The decomposition reveals operational and design aspects of manufacturing system design (e.g. machine design aspects and scheduling aspects). The MSDD shows how both aspects

influence each other, i.e. how a design decision may deter or support an operational policy (e.g. machines with long changeover times will not allow for small lot production).
- Providing path dependency for decision making during system design (design decisions on the left side affect design decisions on the right side not vice versa).
For example: reducing throughput time requires capable processes and predictable time output. If these prerequisites are not satisfied, reducing throughput time e.g. by cutting inventory can be very dangerous. This problem is expressed in the MSDD by stating that both quality (DP-111) and predictable output (DP-112) influence the achievements of reducing throughput time (see dotted lines between FRs and DPs in Figure 2).

5 COMPARISON OF PROCEDURAL DESIGN AND MSDD

The procedural design leads to physical entities on the shop floor and guides the design process for each of the entities. However, the procedural design methods do not provide a clear structure of system objectives, which may result in local optimization at the expense of overall total cost effectiveness.

The MSDD states the functional requirements of a manufacturing system design. The FRs are independent of the specific physical entities such as manufacturing stations or cells. The stated objectives have to be considered in all areas of the manufacturing system. The goal of the MSDD is to structure these objectives. The MSDD does not guide the designer to physical entities, but forces her to think about the objectives, she wants to achieve. Thus, the MSDD is not a manufacturing system design approach in itself, but more a decision support tool to be used along with a procedural design method.

The following section explains how the MSDD can be used together with a top-down procedural design approach.

6 COMBINATION OF PROCEDURAL DESIGN AND MSDD

The proposed combination of the MSDD with procedural design will be both qualitative and quantitative. Some objectives are hard to measure particularly during the early stages of system design. For example, the requirement DP-112 "Reduction of throughput time variation" aims to satisfy the FR-112 "Deliver products on time." Further decomposition of this objective leads to the layout of visible factories, standard methods to solve problems, training programs etc. While those objectives are hard to measure they place constraints to the procedural design phases from rough planning to execution. Thus, the first step in the combination of the MSDD with procedural design is to consider the objectives of the MSDD as design requirements or constraints for the procedural design phases. The quantitative integration uses performance measurements to verify if the outcome of a procedural design phase meets the system objectives as stated in the MSDD. The general approach is shown in Figure 3.
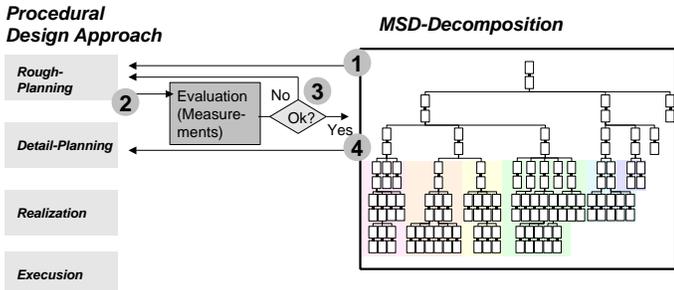
Figure 3: General procedure of linking procedural design with MSDD.

There are basically 4 steps, which must be performed for the combination of the decomposition approach and the procedural design approach (Table 1):

Table 1: four steps in combining the decomposition approach and the procedural design approach.

Step	Content	Example
1	MSDD defines system objectives (FRs) for the first phase of the procedural desisgn (preparation phase).	FR-T21: "Define Takt Time"
2	The preparation phase of the procedural design must must satisfy the objectives derived from the MSDD.	
3	The evaluation checks, if the objectives stated in the MSDD are achieved.	Has takt time been defined? Yes/No
4	Repeat steps 1-3 for the next phase	

In step (1), the MSDD defines system objectives, which have to be considered in the phases of the procedural design approach. It is important to note that the MSDD does not define all objectives for the procedural phases. The procedural phases must consider the specific application, while the MSDD is application independent. In step (2), the system designer follows the tasks of the next procedural design phase as laid out in section 3. In step (3), it is evaluated if the objectives derived in step (1) are satisfied in step (2). This can be a simple yes/no check or a quantitative measure. If the objectives are not satisfied, the designer has to repeat step (2). If the objectives are satisfied, the design proceeds to step (4) and the objectives for the next procedural design phase are derived from the MSDD until the design is completed.

Note that the measurement evaluates if and how well the objectives are achieved i.e. the FRs. The rationale being that measurement must be aligned with the FRs of the system design [Cochran, Kim, Kim, 2000].

There are several performance measures for the evaluation of company performance and shop floor performance. The most often used measurements in Europe are derivatives of the Overall Equipment Effectiveness (OEE) [Al-Radhi]. The OEE is the product of utilization, performance efficiency, and quality rate. The utilization is composed of measurements according to VDI 3432.

In general, the given sets of performance measurables are well suited for the optimization and detailed design of sub-systems.

However, it is very difficult to evaluate, if the high-level objectives of the company are met (such as stability, quality level, effectiveness of operators). The MSDD states those objectives, their dependencies and their decomposition. We therefore linked the procedural design with the MSDD through measures. This allows the alignment of high- level company objectives with the measurables. It is important to note that not all measures are quantitative. There are several objectives during the design phases which simply require a yes/no answer (e.g. has takt time been defined yes/no). The planning and design objectives are often very broad, particularly during the early stages. In theses instances, the MSDD defines objectives, which the procedural design has to satisfy. The next paragraph describes the combination of the procedural design and the MSDD in more detail.

6.1 COMBINATION OF PROCEDURAL DESIGN AND MSDD THROUGH PERFORMANCE MEASUREMENTS

The following section will show how the measurements can grade the achievements of the MSDD objectives in the design phases of rough planning (ideal and realistic), detailed planning, realization and execution (see section 3).

The basis for manufacturing system design is a thorough analysis of the product structure, and existing reusable equipment. Market research should also analyze demand volume and cost structures for product and manufacturing facilities. The preparation phase further elaborates on these information and builds the basis for the rough planning.

The design steps for the **preparation phase** are very broad. The MSDD basically states two objectives to be considered in this phase: "Manufacture products to target design specifications", which forces to select capable process equipment. Furthermore, the MSDD emphasizes the importance to determine the customers of the system (internal or external). The idea behind this step is to define the takt time of the system and to pace the system according to takt time [Linck, Cochran, 1999]. However, there are no performance measurements, which can actually measure the achievements of these objectives. It is more a question of yes/no, if the objectives have been considered during the design phase.

The goal of the next design phase is to elaborate an **ideal design**. The MSDD states several objectives, which occur in the decomposition branches of predictable output, mean throughput time reduction, and direct labor. The emphasis for predictable output is to design a system, which exposes any abnormalities during production, provides means to solve the problems immediately and includes training of the operators. Mean throughput time reduction requires proper settings of operational parameters (such as takt time, machine cycle time, etc.) and subsystem configurations. The labor branch stresses the importance that operators work loops must take place at an early stage of system design to achieve high worker efficiency. The **realistic design** places constraints to the ideal design and may reduce possible alternatives. The designer also elaborates in more

detail on the ideal design. Figure 4 illustrates where the objectives for the phases are in the MSDD. The application example in section 7 states the FRs explicitly.

The following paragraph illustrates in more detail the procedure for the labor branch. The performance measures for the FRs are included in each FR-box.

- ◻ (light gray) *preparation phase*
- ◼ (medium gray) *ideal design phase*
- ■ (black) *realistic design phase*
- ◼ (dark gray) *detail design phase*
- ◼ (gray) *execution phase*
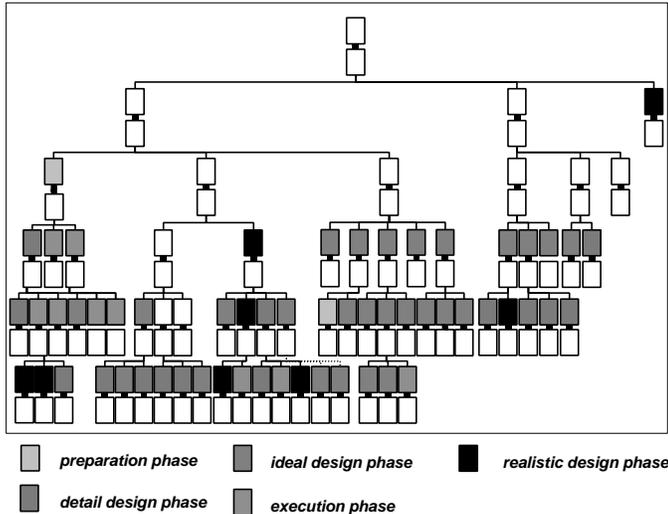
Figure 4: objectives derived from the MSDD for the different phases of procedural design.

The MSDD defines more objectives to be achieved in the **detailed design** mainly in the branches of quality (FR-Q11, FR-Q12x), identifying and resolving problems (FR-R11x, FR112x, FR113x) and work loop design (FR-Dx). The **execution phase** adds objectives mainly in the quality branch (FR-Q12, FR-Q13, FR-Q3x), and the predictable output branch (FR-122, FR-13x). The measures for the last two phases become more quantitative than for the first three phases, but are still very broad. The reason is that MSDD is not laid out for a particular design, but aims to be applicable for a wide range of systems for discrete part manufacturing.

7 APPLICATION

The application example deals with an assembly line for hoses. The original line design is shown in Figure 5. The line exposed several problems: defect rate of about 2,700 ppm, frequent line stoppages due material shortages, unbalanced work among the operators leading to high percentage of idle time, high absenteeism due to monotonous work content.
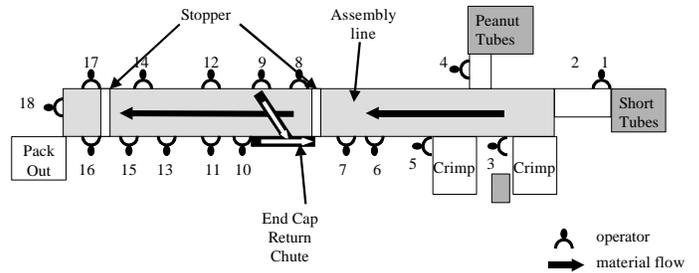
Figure 5: original design of hose assembly line

The redesign started with a thorough analysis as suggested by the preparation phase. The objectives derived from the MSDD for this phase were FR-111 "Manufacture products to target design specifications" and FR –T121 "Define takt time." FR-111 forces to select appropriate production processes to manufacture quality products. The existing processes could satisfy this requirements.

Takt time is the quotient of available production time per time period over total demand per time period. The following table shows the takt time for different operating patterns and number of cells.

Table 2: Takt Time calculations

Work Schedule	Takt Time
a) 1cell, 1 shift (same as line)	6.2
b) 2 cells, 1 shift	12.4
c) 2 cells, 2 shifts	23.3

A takt time of 20 seconds is very short for manned manufacturing cells, since it will limit operators to perform multiple tasks. The cycle time of the original assembly line was 7.3 seconds limiting the operators to do basically a single operations such as tightening a screw. Thus, it was decided to design two assembly cells operated in 2 shifts with a takt time of 23.3 seconds each.

The ideal design phase had to satisfy several objectives from the MSDD to enable fast detection of disruptions (FR-R112), ensuring predictable output by guaranteeing material availability (FR-P141 and FR-142), subsystem design to avoid production disruptions (FR-T51 to FR-T53), designing balanced operator work loops.

The most challenging part of this design phase was to balance the work content among the operators. The objective was to design the work content of all operators as close to takt time as possible and to avoid any significant idle time during one cycle (FR-D2). The shown configuration also supported the other objectives. The operators could very quickly recognize production disruptions, since all operations were very close together allowing for good communication and fast feedback. Material supply to the cell was standardized. Every 20 minutes the material handler would deliver material for 50 more parts. This ensured that the cell never starved and also didn't allow the operators to work ahead. The

material was fed to the stations from the outside so that the operators were not disrupted in their work.

The realistic design further elaborated on the ideal design. The MSDD defines more detailed objectives with respect to machine design (FR-P12) and operators capabilities / training (FR-D12). Training became an important aspect in the given design task. All operators had to be able to perform basically all tasks so that the operators can support each other within the cell. The leak test had to be shared by both cells due to a management imposed constraint. Figure 6 shows the schematic design after this design phase.
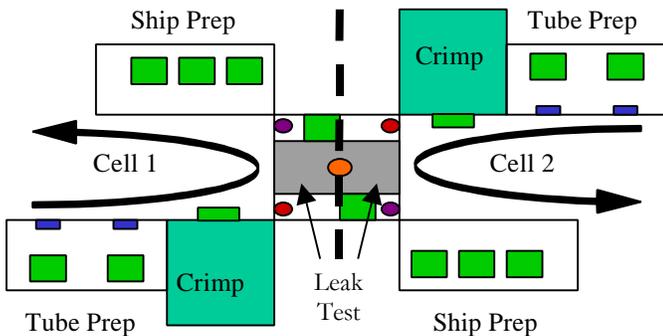
Figure 6: ideal schematic design of two assembly cells

The MSDD objectives for the detailed design further elaborate on the idea to ensure fast feedback (FR-R11x), standardization of all operations including support activities such as material supply (FR-R12x, FR-P131), detailed design objectives for the work loop design of operators (FR-D11, FR-D2x). The importance of those objectives is often underestimated during the design stage. The detailed design of the operators work content is mandatory to ensure predictable output and – even more importantly – to support continuous improvement. Only standardized operations expose disruptions and waste, which can then be eliminated. The MSDD states how such low-level decisions affect the achievement of high-level system objectives. Unpredictable output due to non-standardized work procedures will ultimately force to buffer against this unpredictability, which then leads to increased throughput time.

The detailed design in the given application was done on the shop floor itself by arranging the equipment according the schematic layout shown in Figure 6. This was possible because the assembly equipment was easy to move and easy to configure.

The additional objectives from the MSDD for the execution phase deal mainly with the quality branch, the achievement of predictable output, and actual scheduling methods to obtain a leveled schedule. However, execution must also ensure the satisfaction of the objectives from previous phases such as following standardized work loops. When the designed cells where put in place and operators started working they hesitated to follow the strict rules of producing in a single-piece flow manner. At one point they wanted to operate the cell in the "traditional" way i.e.

building batches at each station. They ran the cell in a single-piece-flow mode and a batch mode for one week each and compared the performance afterwards in terms of defect rate and efficiency. It turned out the single-piece-flow mode was superior in both categories. The improvements of the redesign are shown in the Table 3.

Table 3: Comparison of before and after redesign.

Measurable	Before Redesign	After Redesign
Floor Space	1500 sq. ft.	320 sq. ft.
Direct Workers	18	12 (3 per cell for 2 shifts)
Man-hours required	~170	96
Avg # of Defects per Month	226	2.5
% Absenteeism	4	0
Throughput time	Variable (~20 min)	72 secs
WIP	Variable (~150)	6 (3 per cell)
Incoming Material	High and variable	50 pieces/20 min
Conveyor	90 ft	none

8 CONCLUSION AND OUTLOOK

The design of manufacturing systems requires the explicit statement of the design objectives and solutions. It is also necessary to offer the designer a tool to link lower level design decisions to higher level system objectives to avoid local sub-optimization. The MSDD provides such a tool. However, it is also necessary to develop a physical hierarchy of the system by providing a means to structure the system in manageable sub-units. The paper elaborates how both approaches can be combined towards a unified design methodology for manufacturing systems. The application demonstrated the combination and showed the potential benefits.

Further applications and field studies are necessary to fully develop the approach particularly integrating physical and computer simulations for the evaluation of proposed designs. The parameters measured during the simulation can be derived from the FRs of the MSDD and can be checked during the simulation run. An extension of the MSDD is a tool to evaluate the present performance of a system to elaborate potential areas of improvement [Chu, 2000]. This work offers a useful extension of the presented approach particularly for the preparation phase.

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