

Rational Design of Process Simulation Models Using Manufacturing System Design Decomposition

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Abstract

Design of computerized process simulation models are often an attempt to mimic workings of an existing manufacturing process with as much precision as feasible so that analysis is optimally useful. This modeling may also be applied to processes that are new and do not have a pre-existing physical example. A methodology from Axiomatic Design called Manufacturing System Design Decomposition (MSDD) is employed to define the functional requirements and the design parameters for the processes which are then employed in the design of the process simulation model. By its very nature, the resultant design is lean since the focus is on the specific functions to be performed necessary to the manufacture of the product at the lowest possible cost. Acclaro DFSS software from Axiomatic Design Solutions, Inc. provides the environment for developing the Axiomatic Design model and Witness software from Lanner Inc. is employed for the simulation environment.

Keywords: *Axiomatic Design, Overmold, Process Simulation, MSDD*

1 Introduction

A new dual-stage overmolding process for the packaging of automotive electronic crash sensors is being developed in a pilot process at TRW Automotive LLC. This activity has coincided with an initial investigation into the application of Axiomatic Design in the definition of manufacturing Functional Requirements for the development of manufacturing processes and simulation models as a part of the DEMS program at Lawrence Technological University.

Dr. Nam Pyo Suh, in a series of papers and books published beginning in the mid-1980's culminating in the publication of Axiomatic Design Advances and Applications, proposed a different methodology for solving this problem of analyzing functional requirements and translating them into product or

process design parameters [1]. Analogous to QFD matrices, Dr. Suh proposed four domains to classify the relationship between, what the customer wants, functional requirements of the solution to these wants, design parameters and processes to fabricate the solution.

The four defined domains are: Customer Domain, Functional Domain, Design Domain and Process Domain and these are shown in Figure 1. What the customer wants, in axiomatic design terms represents the Customer Domain. Voice of the Customer elements are then translated successively from wants into Functional Requirements, then into the Design Parameters that satisfy the Functional Requirements and then into the process domain which realizes the physicality of the Design Parameters.

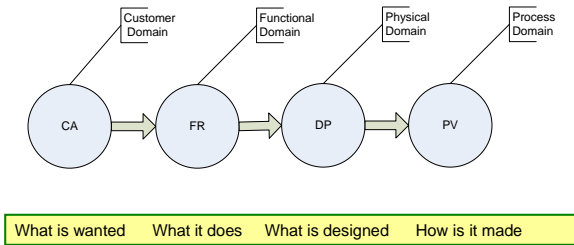


Figure 1: Axiomatic Domains

With this approach, a relationship can be established between the customer want of “reliable safety at minimal cost”, the design and optimization of the manufacturing process and in the end, delivery of a product that provides reliable safety to the consumer at a reasonable cost.

David Cochran and others proposed specific application of functional decomposition and related design parameters to manufacturing system design. Cochran, and his associates described this “Manufacturing System Design Decomposition”, MSDD, approach in a series of published papers [2]. Within the MSDD methodology, the main focus is on the decomposition of functional requirements and the association of design parameters. Other aspects of Axiomatic Design such as the Information Axiom are not explicitly employed. Although Cochran and his associates state that this approach is most suitable for medium to high volume manufacturing enterprises, it is not clear if they contend that this is due to the limited resources available to smaller businesses, or in recognition that by their nature, small enterprises are more intimate with their processes. They suggest that as a practical matter, it is difficult for enterprises to develop manufacturing systems that satisfy their strategic business objectives, quoting Hopp and Sherman’s perspective that too much of the focus in manufacturing development is on the individual process aspects, losing sight of the overall business objectives. For example a CNC milling center may provide a manufacturing capability in replacing an existing manual milling center without being firmly linked to an over-all enterprise strategy which might be to replace machined metal components with plastic injection molded ones. Inherent to this argument is the perspective that business planning must propagate from the top of the organization downwards and not conversely, from the bottom up.

MSDD philosophy dictates that the following four conditions shown in Table 1 must be met in order for

a manufacturing system to satisfy corporate objectives:

Table 1: RULES OF MSDD [2]

1.	Clearly separate objectives from the means of achievement
2.	Relate low-level activities and decisions to the high-level goals and requirements
3.	Understand the interrelationships among the different elements of a system design
4.	Effectively communicate this information across the organization

When manufacturing consists of more than a single step, the sequence of the steps involved in the completion of the final product becomes critical and it is by its very nature that this sequence produces functional coupling. As Almstrom and Martensson indicate, with the exception of their paper, this coupling has not been assessed or discussed [3]. Using a case-study example of three connected machining cells, they define a categorization of naturally occurring manufacturing based functional couplings to shed some light on manufacturing coupling as is shown in Table 2.

Table 2: MANUFACTURING-BASED FUNCTIONAL COUPLINGS [3]

1	Sequence induced couplings
2	Design Parameter-induced sequence
3	Product property constraint
4	Resource integration prompted coupling
5	Multiple DP instances

Ultimately Martensson and Almstrom conclude that uncoupled manufacturing systems do not and can not exist. In their words it is “unthinkable” since there would need to be total independence throughout the sequence of manufacturing process steps.

In a sequence of process steps, the FR’s are typically performed in a particular order, i.e., the hole must be drilled before it can be threaded. In another example, surface grinding can only be performed after a metal component is machined on a lathe. The process steps cannot be reversed in order. For a dual-stage overmolding process, molding of the elastomeric material around a nylon substrate would necessitate a specific sequence of molding processes. This sequence is fixed by the nature of the materials and their functions.

A single dual material injection press or two independent single material injection presses may be employed for the Overmolding process, one for each polymer material, each having a mold set with multiple cavities. Each cavity forms a unique final part. This simple example of multiple instances of a DP to satisfy a single FR, results in multiple parts that are similar but have different dimensional characteristics.

The same situation occurs frequently throughout many types of manufacturing processes. Individual electronic printed circuits are frequently grouped into a larger circuit array or panel for ease of processing and to maximize equipment utilization. The array of circuits would at some stage be divided into the individual circuits that comprise each end device. A functional tester might perform a performance test simultaneously on multiple parts. Each of these represents this type of coupling where one FR is satisfied by multiple DP's.

Cochran and his associates apply MSDD to the Return on Investment metric, as did Suh before them [2]. The authors acknowledge the criticisms of this metric by Kaplan and others [2]. The authors contend that simply because a metric is often employed for ill-considered short-term gain, that by itself does not diminish the utility of the metric. Accordingly, they set their highest level Functional Requirement to be "Maximize Return on Investment."

Houshmand and Jamshidnezhad, in their application of MSDD to development of lean production systems define their first level of Functional Requirement as "Maximizing Profitability" without defining what that means. "Maximize long-term return on manufacturing investment" does not appear until the second level in the decomposition. The Design Parameter associated with that Functional Requirement is to "Design manufacturing system based on lean philosophy" [4].

Kim also considers manufacturing from a system architecture perspective as associated with practice of product design. His criticism of conventional process design activities is that the focus becomes one of inputs, processes, outputs and the supporting capital equipment while neglecting consideration for those other manufacturing operations that also contribute to total product cost. In his decomposition matrix, Kim sets his highest level Functional Requirement as "Maximize long-term Return on Investment." Kim groups his decomposition of Functional Requirements and Design Parameters into five major

classifications or branches: Quality, Problem solving, Predictable output, Delay reduction, Operational costs and Investment [5]. By comparison, Cochran's major branches are; Quality, Process throughput, Reduce waste and Minimize investment [2].

Whether the metric being optimized is to maximize Return on Sales or Return on Investment, ultimately the same considerations or Functional Requirements appear through the decomposition branches, although they may occur at different decomposition levels. In a general sense, functions are required that support the need to increase sales and to decrease costs. Where they appear in the decomposition reflects the manufacturing system design methodology at hand.

While these authors promote the benefits that may be derived from the application of MSDD in relating high-level organizational objections to low-level activities, the majority of their system decompositions only describe the high-level production system architecture. Their focus is on a general model definition for the production system architecture that defines quality systems, production planning and inventory management, maintenance systems and production capacity capitalization.

By comparison, Gu, Rao and Tseng do carry the decomposition forward to a level sufficient to define specific workstation or machine functions. Additionally they map through the three domains that follow the Customer Attribute domain so that the full Functional Requirement, Design Parameter, and Process Variable set are described [6].

It is also interesting to note that while most of the authors discuss the decomposition of Functional Requirements and physical domain Design Parameters, few authors or practitioners include the PV from the process domain, in their analysis. This is similar to Quality Function Deployment where the first house, the House of Quality is used extensively and the remaining houses (matrices) such as Design, Process and Production Control are employed only infrequently.

2 Design Information Convergence and Fusion

It is apparent from the review of Axiomatic Design and Quality Function Deployment that there is a commonality to the management and manipulation of design information. At the same time it is clear that the Functional Requirements and Design Parameters discussed are the same Functional Requirements and parameters employed in Failure Mode Effect Analysis. Mohsen and Cekecek [7] recognized this

relationship as well as the potential for linking into Functional Requirements Specification, P-Diagrams and Test Development Strategy. The P-Diagram with its analysis of Control Factors, Noise Factors, Input and Response has importance at two levels: use in signal optimization and also in development of the noise factor management strategy which defines optimization.

Englehardt [8] described a model for product and system improvement which integrated Axiomatic Design, the Ishikawa’s seven quality control tools and designed experiments. While Englehardt lists some of these tools, he does not provide a description

of the interrelationship between these tool and Axiomatic Design or how that integration would benefit the user.

Failure Mode Effect Analysis (FMEA) and Axiomatic Design are genetically linked. AD decomposes Functional Requirements and Design Parameters into process variables. In comparison, the FMEA defines the parameter and then the function. These functions are correspondingly associated with effects for that failure mode and a quantified risk assessment for each failure mode. The following example shown in Figure 2 provides the basic structure of the FMEA.

Function	Potential Failure Mode	Potential Effects of Failure	Severity	Potential Causes of Failure	Occurrence	Current Design Controls	Detection	RPN	Recommended Actions	Responsibility and Target Completion Date	Action Taken
FR 1.2.1.5 Inject plastic into cavity	Insufficient volume injected	Insufficient part strength	8	Screw position sense variation		Fill volume based on time	7	168	Add mold cavity pressure sensor	Miklos Molnar 10 July 2012	

Figure 2: Process Failure Mode Effects Analysis Example

In this example, a function is identified as Functional Requirement FR 1.2.1.5 Inject plastic into mold.

This is identified with a potential failure mode of “Insufficient volume injected”. In order to counter this failure mode, a Design Parameter is specified to incorporate mold cavity pressure sensing to ensure that the mold cavity is properly filled. This design criterion is then fed back into the Axiomatic Design model. Essentially, the design can be optimized and risk managed by employing Axiomatic Design to define the Functional Requirements and Design Parameters, and then employing Failure Mode Effects Analysis on that product or process design.. This can further provide the model definition for simulations such as Finite Element Analysis (FEA) and computer based process simulation modeling.

3 Simulation

The application of the Axiomatic Design’s MSDD methodology provides a rational means for formulating the simulation objective or problem statement since this can be drawn from the high-level

Functional Requirement. This FR represents the true objective of the organization. As an example, the highest organizational objective might be to maximize the Return on Sales. Carson and Banks developed a model for simulation model development [9]. As shown in Figure 3, Step 1 (indicated by an circled number “1”) in the Carson-Banks model Problem Formulation directly flows from level FR0 in the Axiomatic Design model. Definition of simulation objectives would correspondingly be drawn from the decomposition of the high-level FR’s into more specific objectives.

For the purpose of illustrating this discussion, a simplified product and production model was developed with FR0 defined as “Manufacture molded module”. Each part being produced, the Dolog, follows the same manufacturing sequence. As shown in Figure 4, the activity of manufacturing a molded module consists of three main decompositions; molding the assembly, mechanical assembly of a fastener, and finally functional testing of the assembly.

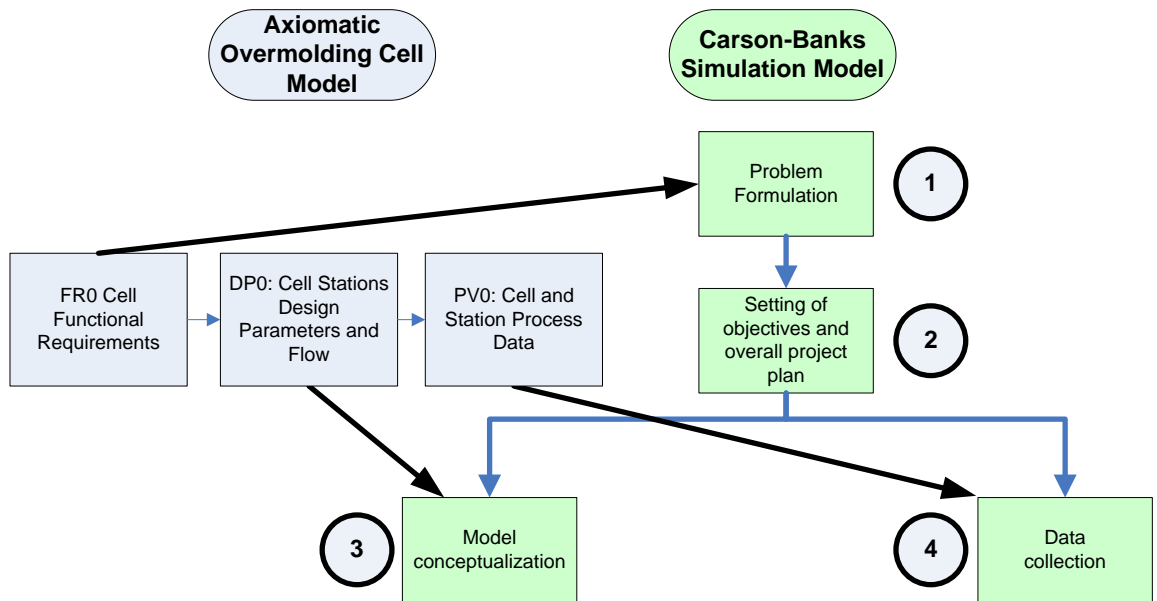


Figure 3: Axiomatic Design and Simulation Model Postulation

0	FR	Manufacture molded module	DP	Lean molding cell that includes molding,	PV	Manufacturing cell with takt time of 4.75 seconds
1	FR	Mold sub assembly	DP	85 Ton Arburg Injection molding station	PV	Molding process takt time of 4.5 seconds
2	FR	Assemble threaded fastener	DP	Screw assembly feeder and station	PV	Assembly takt time of 3.5 seconds
3	FR	Test part function	DP	Functional tester	PV	Testing takt time of 3.1 seconds

Figure 4: Top Level Model Decomposition

Functional Requirements FR1 through FR3 are decomposed to a level of greater detail as and this becomes the definition for the simulation model which will be implemented in Lanner's Witness program [10]. Acclaro DFSS software from Axiomatic Design Solutions, Inc. is employed to manage the decomposition of Functional Requirements, Design Parameters and Process Variables [11]. Acclaro also has the capability to produce a flowchart from the Axiomatic Model. This is demonstrated at this high level in Figure 5 where each step in the flow chart correlates to an icon on the simulation model.

In each case, for each work station, the FR defines the Functional Requirement for the process and the DP, design parameter, describes the work station characteristics that satisfy that function. Similar to

the act of traversing from the trunk of a tree out into its branches, further decomposition of FR1, will provide an increasingly detailed break-down of the function. Witness facilitates the application of one of several machine types when modeling each station. As shown in Figure 6, by right-button selecting the DP1_Molding_Station icon, Witness takes the user to the detailed description for the machine being modeled. One of the fairly simple machine classes, a "General" type machine might be selected for this station. This provides the possibility of one or more inputs being processed into one or more outputs. In this case, eight units of nylon and eight units of elastomer combine to form eight finished Dolog. The processing cycle time is 0.6 minutes for each group of eight Dolog.

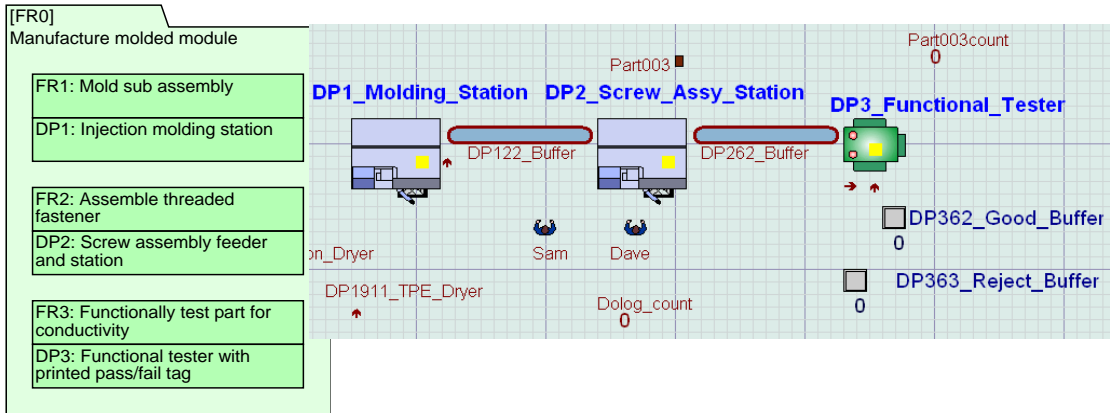


Figure 5: Flow Chart and Model Layout

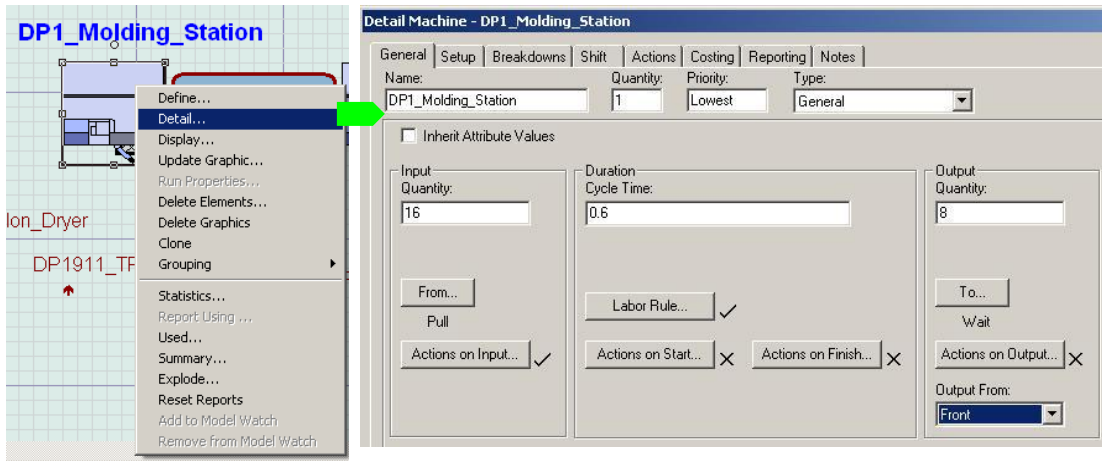


Figure 6: General Machine Selection

From examination of the variety of alternatives for Witness machine classification in Figure 7, we see the option of “Multicycle Machine” in the menu of choices.

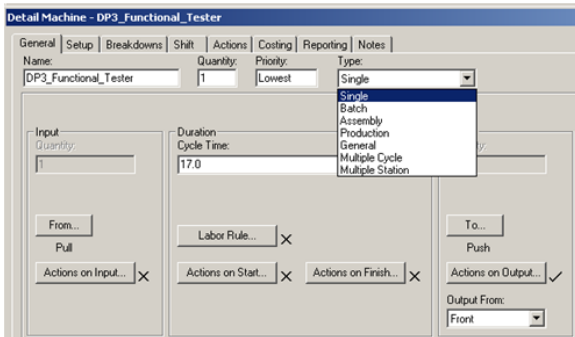


Figure 7: Machine Type Classification

It is with this selection, that it is possible to take full advantage of the power inherent in Witness software, and in fact, to fully integrate the powerful design potential of Functional Requirements decomposition into the design of the manufacturing cell with the optimization potential provided by Witness.

One could easily treat the molding process with an overall cycle time. Alternatively, this process could be broken down into individual steps for that work station with individual time, labor, and cost elements. This is similar to the approach taken in early time and motion analysis where in one classic example, Frederick W. Taylor studied the time elements for a laborer shoveling coal in order to determine the optimum motions and shovel size.

In the same manner, the molding process can be decomposed into individual Functional Requirements

which provide increased functional specificity and provide a means to identify time, cost and breakdown for each element.

The molding process FR1, has been decomposed, that is, broken down, into increasingly specific sub-components so that the molding process can be examined in greater detail. As shown in Figures 8 and 9, FR1 Mold Sub Assembly can be divided into FR1.1 through FR1.11. These comprise the main activities of the dual shot injection molding process. Further decomposition for FR1.2 and FR1.7 is also possible. For each workstation function in Mold Sub Assembly, we can see both the Design Parameters and the Process variables such as time components allocated to each function. This becomes useful during the progression into simulation model

development since the optimization of the process may focus on cooling time or pack and hold time to increase workstation throughput.

What is the source for the time elements in the Process Variable (PV) values? If this is an existing process, it may be as simple as collecting data from the machine itself, or by conducting time and motion studies. New processes, where there is no preexisting empirical world to study represent a different challenge. By decomposing the molding process, those building the simulation model can use standard time data for actions such as opening and closing the press, etc. In this way, information from analogous time elements can be employed to improve simulation model efficacy.

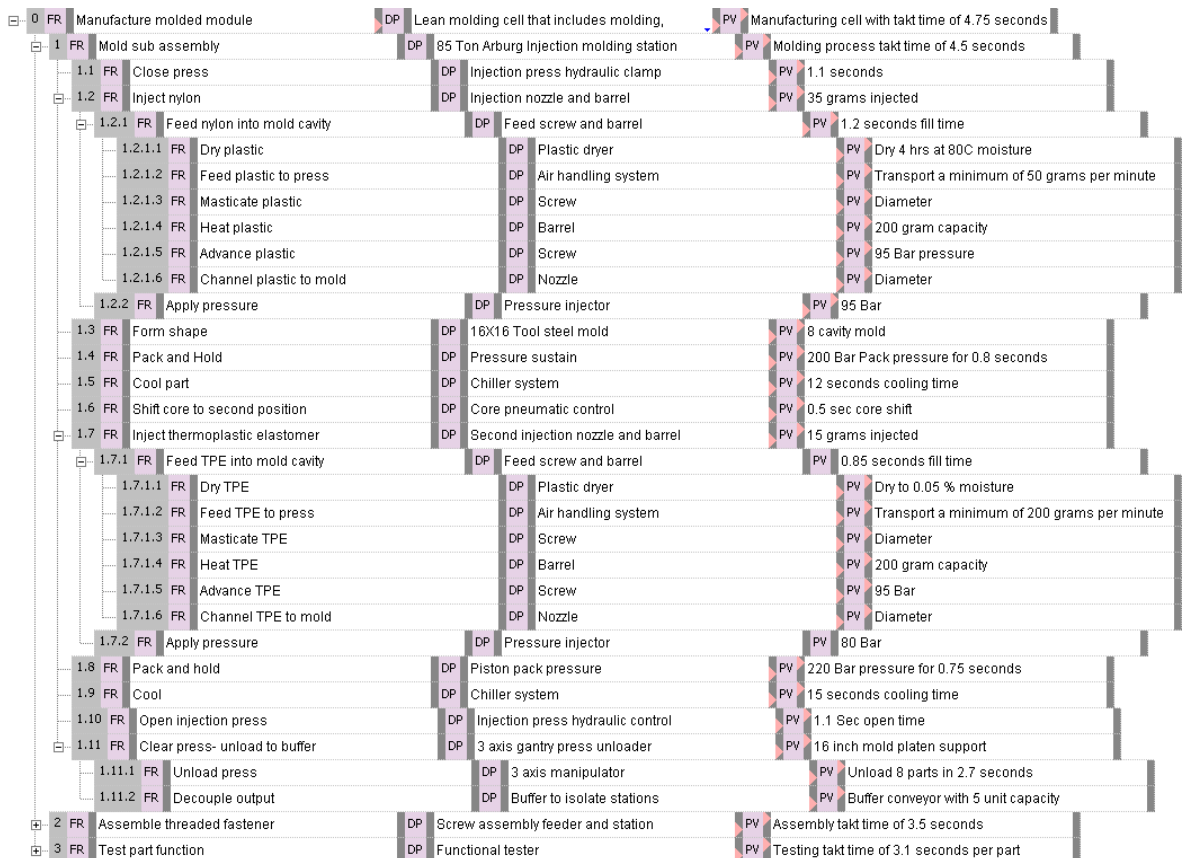


Figure 8: Decomposition of FR1 - Mold Sub-assemblies

Acclaro Axiomatic Design Process Decomposition

Witness Multicycle Machine Simulation Definition

0	FR	Manufacture molded module	DP	Lean molding cell that includes molding,
1	FR	Mold sub assembly	DP	85 Ton Arburg Injection molding station
1.1	FR	Close press	DP	Injection press hydraulic clamp
1.2	FR	Inject nylon	DP	Injection nozzle and barrel
1.3	FR	Form shape	DP	16X16 Tool steel mold
1.4	FR	Pack and Hold	DP	Pressure sustain
1.5	FR	Cool part	DP	Chiller system
1.6	FR	Shift core to second position	DP	Core pneumatic control
1.7	FR	Inject thermoplastic elastomer	DP	Second injection nozzle and barrel
1.8	FR	Pack and hold	DP	Piston pack pressure
1.9	FR	Cool	DP	Chiller system
1.10	FR	Open injection press	DP	Injection press hydraulic control
1.11	FR	Clear press- unload to buffer	DP	3 axis gantry press unloader
2	FR	Assemble threaded fastener	DP	Screw assembly feeder and station
3	FR	Test part function	DP	Functional tester

	Cycle name
1	FR1.1 Close Press
2	FR1.2 Inject Nylon
3	FR1.3 Form shape
4	FR1.4 Pack and hold
5	FR1.5 Cool part
6	FR1.6 Shift core to second position
7	FR1.7 Inject TPE
8	FR1.8 Pack and hold
9	FR1.9 Cool
10	FR1.10 Open Injection Press
11	FR1.11 Unload to Buffer DP 1.11.2

Figure 9: Simulation Model - Multicycle Machine Configuration

By employing Probability Density Functions in Figure 10 in place of the fixed cycle time elements as shown in Figures 6 and 7, the natural process variability can be more thoroughly explored. In the first instance, the model has been defined with fixed time elements which will make the model deterministic, that is, there is no natural variability in the time element. When the time elements for each cycle in are modeled as fixed time elements, each time the model is run, and for each part produced the

takt time is the same. This type of model would not effectively simulate the natural variability of the real world experience where differences for each mold cycle would result in cycle time variability. This model can be improved to more closely mimic the actual manufacturing cell by employing Probability Density Functions of historical data such as the normal distributions shown in Figure 10 so that with each execution of a cycle the time elements are selected statistically.

Detail Machine - DP1_Molding_Station							
General Setup Breakdowns Shift Actions Costing Reporting Notes							
Name: DP1_Molding_Station		Quantity: 1	Priority: Lowest	Type: Multiple Cycle			
<input type="checkbox"/> Inherit Attribute Values							
	Cycle name	Input			Duration		
		Quantity	From	Actions on Input	Actions on Start	Labor Rule	Cycle Time
1	FR1.1 Close Press	8	Pull	Y	N	Y	NORMAL (0.018,0.00098,103)
2	FR1.2 Inject Nylon	0	Wait	N	N	N	NORMAL (0.02,0.00098,104)
3	FR1.3 Form shape	0	Wait	N	N	N	0.0
4	FR1.4 Pack and hold	0	Wait	N	N	N	NORMAL (0.013,0.00098,105)
5	FR1.5 Cool part	0	Wait	N	N	N	NORMAL (0.2,0.00098,106)
6	FR1.6 Shift core to second position	0	Wait	N	N	N	NORMAL (0.008,9e-005,107)
7	FR1.7 Inject TPE	8	Pull	Y	N	N	NORMAL (0.014,0.00098,108)
8	FR1.8 Pack and hold	0	Wait	N	N	N	NORMAL (0.0125,0.00098,10)
9	FR1.9 Cool	0	Wait	N	N	N	NORMAL (0.25,0.00098,110)
10	FR1.10 Open Injection Press	0	Wait	N	N	N	NORMAL (0.018,0.00098,111)
11	FR1.11 Unload to Buffer DP 1.11.2	0	Wait	N	N	Y	TRIANGLE (0.04,0.045,0.05,1

Figure 10: Station DP1 - Statistical Time Elements

Having produced this level of workstation design detail, using MSDD, this decomposition detail fits into the description of the Multicycle Machine. Each Function has a corresponding specific cycle in the Witness Multicycle Machine. An advantage to this approach is that it is possible to evaluate the affect of variation of each individual time element independent of each other. For example, it might be necessary to explore changes in the FR1.4 Pack and Hold time to evaluate improvements to the molding process yield since holding longer might improve dimensional stability. Or it might be of interest to evaluate the economic impact on total product cost from implementing a more expensive and faster robot on load and unload times.

Just as FR1 was decomposed into detailed Functional Requirements, FR2 Assemble Threaded Fastener and FR3 Functional Test can also be decomposed into more specific and discrete Functional Requirements and analyzed to greater detail.

4 Conclusions

The objective of this paper has been to demonstrate the interrelationship of rational manufacturing process design using the Manufacturing Systems Design Decomposition methodology and process simulation modeling. By focusing on specific functions to be performed that add value, the simulation model design focuses on the lean process requirements rather than being based upon the more commonly utilized “tribal knowledge” approach.

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