From Representation of States to Description of Processes

Dimitris Papanikolaou
Massachusetts Institute of Technology, USA
dimp@mit.edu

Abstract

Introduction of digital technologies in architecture has generated a great amount of hesitation and criticism about the role of design and its relation to the artifact. This confusion seems to stem from the dual nature of design as representation of the form and as a description of its production process. Today architects urge to adopt digital tools to explore complex forms often without understanding the complexity of the underlying production techniques. As a consequence, architects have been accused of making designs that they do not know how to build. Why is this happening today? It seems that while technology has progressed, the design strategy has remained the same. This paper will deal with the following question: *What matters in design?* The paper will reveal fundamental problems, attempt to answer this question, and suggest new directions for design strategies today. The conclusion of this paper is that digital design should also aim to describe process of production rather than solely represent form.

1. Introduction

1.1. What is the role of design?

According to Herbert Simon sciences are classified into natural and artificial[1]. Natural sciences describe the natural world. Sciences of the artificial describe artifacts of human intervention in the natural world; artifacts are conceived by design. Architecture is a science of the artificial; it is the science that describes edifices that will be built by human intervention in the natural world. The word *intervention* includes the technology that the human mind will use to create the artifact. The word *natural* emphasizes that the purpose of the design is to describe something that will be produced in the physical world. Therefore, in architecture there is a close relationship between design description and production means. The question then is: what matters in design? Is it the description of the artifact or the description of the process to make the artifact? But before asking this we should perhaps first query on the nature of the artifact: when does the artifact start to exist, is it during design or during production? To answer that we have to carefully trace the processes that bring the artifact into life; we will call this is the *value chain.* By observing how the structure of the value chain has changed in time we shall be able to draw conclusions on the current role of design.

1.2 The value chain and its role in performance of production

The value chain, a term coined by Michael Porter[2], but definitely explored before by Taiichi Ohno[3], and later by James Womack and Daniel Jones[4], describes the thread of all the processes and resources that are necessary to bring the artifact to life, from design to

---

[1] Simon, Herbert A. The Sciences of the Artificial - 3rd Edition. The MIT Press, 1996. 5

[2] Porter, Michael E. Competitive Advantage: Creating and Sustaining Superior Performance. Free Press, 1998.

[3] Ohno, Taiichi. Toyota Production System: Beyond Large-Scale Production. Productivity Press, 1988.

[4] Womack, James P., and Daniel T. Jones. *LEAN THINKING : Banish Waste and Create Wealth in Your Corporation*. Simon & Schuster, 1996.

production. It starts from conceptualization, procurement of raw amorphous matter, transformation of matter into building components, and finally assembly of the components to form the actual artifact. On every step of the chain, processes add value to the artifact and gradually turn the amorphous disordered matter into ordered form. *Value adding* processes are the processes which embed *design information* into the matter[5]. There are two main types of value adding processes: *transformation* processes and *aggregation* processes. Transformation processes change the form or the state of materials (fabrication) to make parts. Aggregation processes put parts together to form larger complexes (assembly). The value chain should not be perceived as a linear structure; instead it is a network often with significant complexity.

The processed artifact embodies and conveys design information from fabrication processes to assembling processes formulating a communication stream between designers, fabricators, and assemblers. For example, a fabricator that follows designer's instructions to form two interlocking parts with a peg and a hole explicitly conveys the assembling instruction to the assembler through the form of these two parts.

The structure of the value chain greatly affects the design of the artifact because it determines the type and amount of design information that can be embodied and conveyed through the value adding processes. For example the physical constraints of the transportation network, the suppliers' resources, the manufacturing tools, and the assemblers' capacity determine the size and shape of the manufactured parts that will flow through the value chain.

Therefore, the position and distribution of the value adding processes in the value chain is a strategic decision. The more concentrated and the closer the value adding processes are to the construction site, the less the noise and constraints of the chain to the artifact are. On the other hand, the more distant the value adding processes are from the construction site, the more vulnerable the artifact is on the noise and constraints of the structure of the network. Compare for example the probability of failure of the production of an artifact whose parts are fabricated by a number of different fabricators located at remote places from the construction site, to the probability of failure of the production of an artifact whose parts are fabricated by only one fabricator located inside the construction site. Clearly the first case is exposed to higher risk of failure. It turns out that the position and relationship of the value adding processes determines the role of design either as explicit or implicit instruction in a value chain. If design is explicit, its purpose is to direct; if design is implicit, its purpose is to indicate. In the previous example it is clear that in the first case the designer needs to explicitly define all design instructions before the production starts. In the second case however, the designer can implicitly define or even modify design instructions during production since all value adding processes are in the construction site. The position and relationship between fabrication and assembly processes in the value chain varied throughout history. A careful observation of their relation reveals important conclusions about the role of the design in each case.

1.3 The traditional and the digital value chain

In the traditional value chain fabrication and assembly took place at the final step of the chain. Both transformation of raw materials to building components and assembly of the building components to formulate the artifact are handled by the *builder* in the construction site. The designer would know *what,* but the builder would know *how*. The traditional value

---

[5] According to Simon, the amount of design information that is embedded in an artifact relates to its entropy; entropy measures the amount of uncertainty of information. See Simon, *The Sciences of the Artificial, 189.*

chain was experienced based: a great amount of decisions was taken on site. Therefore, design in the traditional value chain was an implicit description of form.

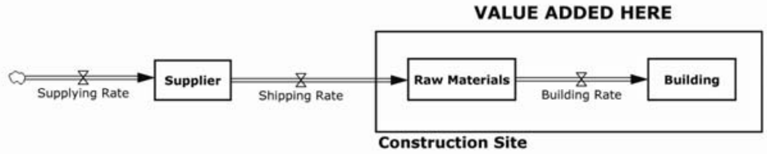


Figure 1. The traditional value chain

In the digital value chain fabrication and assembly take place at different steps in the chain. Now, the transformation of raw, amorphous materials into building components takes place in the middle of the chain by the *manufacturer* but the assembly of the components takes place at the end of the chain, by the *assembler*. The designer needs to know both *what* and *how* and instruct manufacturer and assembler. The digital value chain is knowledge based: all decisions have to be taken before production starts. Therefore, design in the digital value chain is an explicit description of processes. For example, the assembler can not use his experience to assemble a number of pre-manufactured parts because the assembly sequence is already determined by the designer. As a consequence, any mistake during design process is irreversible if manufacturing of parts has taken place.

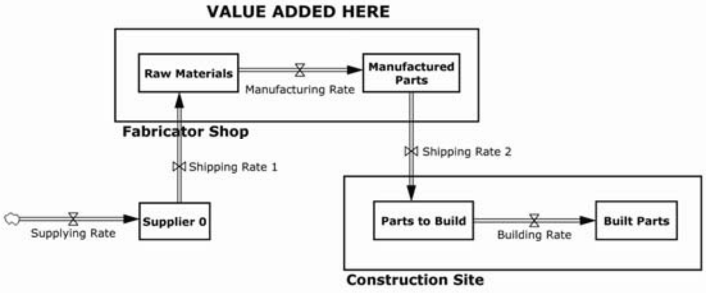


Figure 2. The digital value chain

1.4 The artifact of the digital value chain: complex assembly

This paper defines the digital artifact as the product of the digital value chain. From this definition follows that the digital artifact has a dual aspect: from one hand, as an object it is a complex assembly of customized parts; from the other hand, as a process it is the result of a complex system of collaborating value adding processes. The relation between these two aspects is that the value processes in the chain follow the assembly description as instructions to produce the artifact.

1.5 The problem of describing the digital artifact

This paper deals with the following question: What matters in the design description of the digital artifact? A proper design description should take into account both aspects of the definition of the digital artifact: description of the assembly structure and description of the value chain structure. A proper design description should therefore provide an insight on *how difficult the production of a digital artifact is*. Difficulty of production is a function of two factors: difficulty of assembly process and difficulty of manufacturing process. This brings a new role to designers of the digital value chain from designers of forms to designers of systems of processes.

This paper's statement is that the role of design in the digital value chain is to explicitly describe the process of production of the artifact rather than implicitly represent the form of the artifact. However, today while the value chain has changed, the design strategy has remained the same. As a consequence, today designers design artifacts that they either cannot build or their cost becomes enormous. Unfortunately, most of these incompatibilities are discovered either during construction, or by building physical mockups with a significant loss in both time and cost, and a disputable reliance.

2. Background

2.1. Previous work on description methods

Previous research in understanding assemblability in architecture has focused on two main directions: CAD modeling (3D, 4D) and Physical Mockups. CAD 3D modeling has been used for modeling assemblies. However, CAD 3D modeling represents the final state of the assembly, when all parts have been put together, but not the process of putting these parts together. Moreover, the order of constraint delivery in CAD models has nothing to do with the actual constraint delivery of the real assembly. As a consequence, by studying a CAD 3D model, the designer can not tell if a design is assemblable, nor he can estimate the difficulty of the assembly. CAD 4D modeling has been used for clash detection during assembly sequence. However, 4D modeling fails similarly to describe actual constraint delivery between parts. Physical mockups have been used during design development to test assemblability[6]. However, there is a significant loss in time and cost. In this fashion, testing is empirical, understanding the solution to the geometrical problem is obscure, and design development becomes intuitive.

If digital manufacturing is a new field in architecture, we should perhaps seek the solution to the problem of description in the disciplines that have been dealing with this field. Manufacturing and industrial management have been long dealing with modeling of both assemblies and production systems. Assembly modeling has been thoroughly studied in mechanical engineering and manufacturing using the *liaison graph*[7]. The liaison graph is a network whose nodes represent parts and connections represents liaisons. An assembly sequence can be explicitly defined as a series of nodes and liaisons. The liaison graph provides a concise and formal method to describe assemblies. For further explanation on

---

[6] Sass, Lawrence, Dennis Michaud, Daniel Cardoso. "Materializing a Design with Plywood", *ECAADE*, Frankfurt, Germany, Sept. 2007.

[7] Whitney, Daniel E. Mechanical Assemblies: Their Design, Manufacture, and Role in Product Development. Oxford University Press, USA, 2004, 45.

Network Analysis methods the reader should refer to the bibliography; it is not the purpose of this paper to explain Network Analysis.

System Dynamics is a methodology coming from Control Theory, originally developed by Jay Forrester[8], for studying and managing complex feedback systems. A feedback system is a system in which information from result of past action is a basis for decisions that control future action. A System Dynamics model is a tripartite network consisting of: states (stocks); processes (flows) that affect states; and decision variables that control processes. System Dynamics have been extensively used in modeling of supply chains to evaluate their performance. For further explanation of how System Dynamics methodology works the reader should refer to the bibliography; it is not the purpose of this paper to explain System Dynamics.

3. Proposal

3.1. Description of the digital artifact as a system of value adding processes

This paper attempts an alternative direction for describing the artifact of the digital value chain. Instead on describing form, the proposed method describes and simulates the network of processes that bring the artifact into life. For example, beginning from a liaison graph we can find a valid assembly sequence and then generate the sequence of processes to bring the artifact into life. Tracing back the predecessors of processes we can reveal the entire value chain. By evaluating the performance of the value chain designers can have a better understanding of the complexity and feasibility of their designs.

4. Methods

4.1. Framework of the proposed model

As an example this paper demonstrates a methodology that consists of the following steps; first, description of the assembly as a directed network of parts; direction of connections indicates constraint delivery. Second, determination of assembly sequence and evaluation of its difficulty using the nodal degree distribution; nodal degree is the number of connections each node has with others. Third, conversion of the assembly sequence into a task sequence. Fourth, execution and evaluation of the task sequence in a System Dynamics model of the value adding processes in terms of time, cost, and risk. In short, the method evaluates the performance of a system of processes on executing a system of tasks. Any artifact that will be fabricated and assembled in a value chain can fit in this description. This method should be considered as a complementary design tool during design development.

The following examples apply to assemblies of planar interlocking parts that are manufactured at custom shapes using three-axis CNC routers. Since the parts are planar, each part can be represented by a normal vector perpendicular to its plane. Three-axis CNC routers cut planar parts perpendicularly to their plane, constraining the cuts to have 90-degree bevel angles. Therefore, two parts can have a connection if and only if they are coplanar or perpendicular. The following rules regarding assemblability are briefly presented:

---

[8] Forrester, Jay Wright. *Industrial Dynamics*. Pegasus Communications, 1961.

Rule 1: two nodes can be connected by a liaison if and only if their normal values have a zero or unitary cross product.
Rule 2: difficulty of an assembly step is determined by the number of links an installed part has with the rest of the subassembly.
Rule 3: a part can be located by another part by one or more liaison connections. If the liaison connections are more than one then their liaison installation vectors must be parallel.
Rule 4: A subassembly is the sum of two or more parts connected by liaison graphs. A subassembly can be represented as a single part.
Rule 5: two parts can be connected by a third part which has a normal value equal to the cross product of the two parts.
Rule 6: if in one part more than one liaisons end, then this part can be installed only after all previous parts have already been installed.

The value chain is modeled in System Dynamics as a chain of *flows* and *stocks*. Flows are controlled by the value adding processes. Stocks represent the current state of the matter that flows in the chain (inventories). Value adding processes control flows and change the state of the matter on every step of the chain. The value adding processes that control the flows are: supplying rate, manufacturing rate and assembling rate. Value adding processes are connected through shipping rates. The assembly sequence difficulty and properties of value adding processes (locations, capacities, etc.) will determine the performance of entire value chain.

4.2 Experiment

The following two experiments illustrate both the problems that designers confronted with conventional design tools and the results of the suggested methodology. The first experiment refers to the design, fabrication and assembly of a chair made from interlocking planar parts. The chair was designed in 3D CAD modeling software (Rhinoceros) and the parts were fabricated from planar plywood sheets in a three-axis CNC router. Modeling of the assembly focused on representing two states of the artifact: the assembled form where all parts are put together and the flattened parts in cut-sheets for fabrication. The assembled form seemed to be a valid configuration of the artifact with no clashes between the solid volumes of the parts. Unfortunately, assembly process stopped at a certain point; installation of parts was impossible due to conflicts in the installation vectors. The designers had no tools to describe, understand, and evaluate the assembly process.

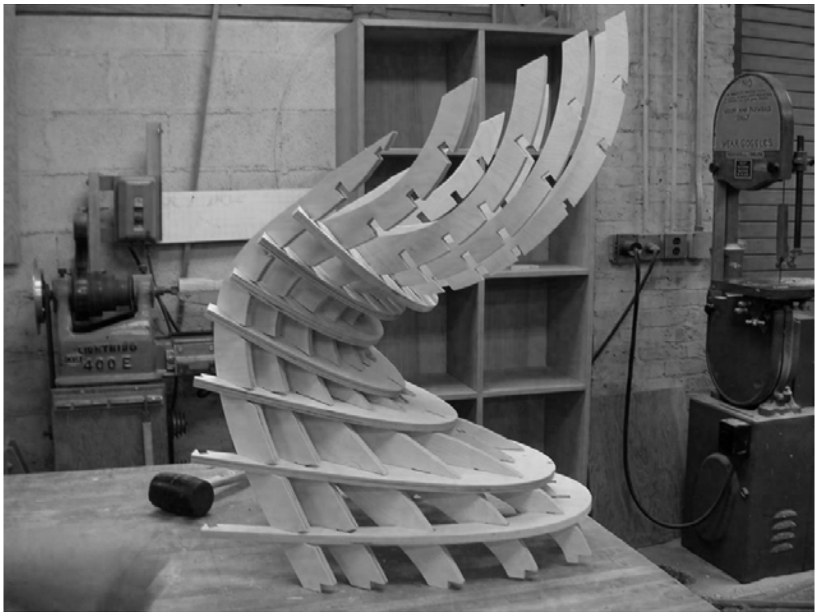


Figure 3. Manual assembly jammed on eighteenth part

A representation of the assembly with the liaison graph clearly shows that the assembly sequence is in fact impossible due to installation vector incompatibility between parts. The analysis shows that assembly should jam at the eleventh step because after that each next part would have to simultaneously connect with nine non-parallel installation vectors with the rest of the assembly. However, real assembly jammed later due to the looseness of the notches of the parts.

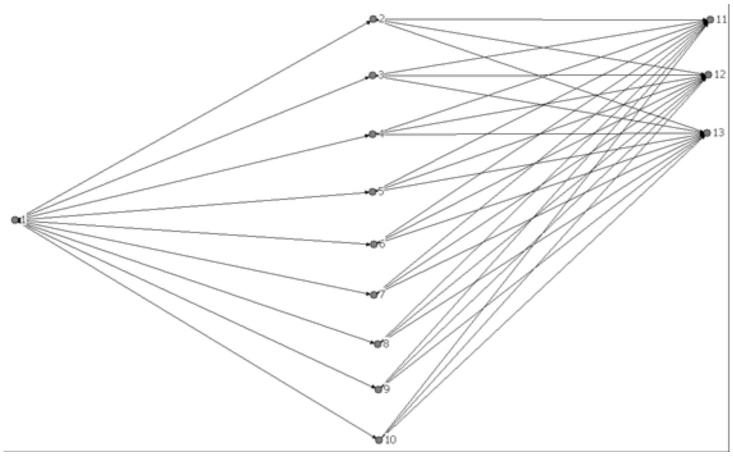


Figure 4. The liaison graph of the chair

The second experiment refers to the design, fabrication, and assembly of a mockup of a façade panel. Design development took place in a parametric 3D CAD modeling software (CATIA). In this case, while the assembly was successful, it proved to be difficult, and took significantly more time than the designer expected. While this example is relatively simple including a small number of parts, it clearly demonstrates the lack of tools that designers need to understand assembly process.

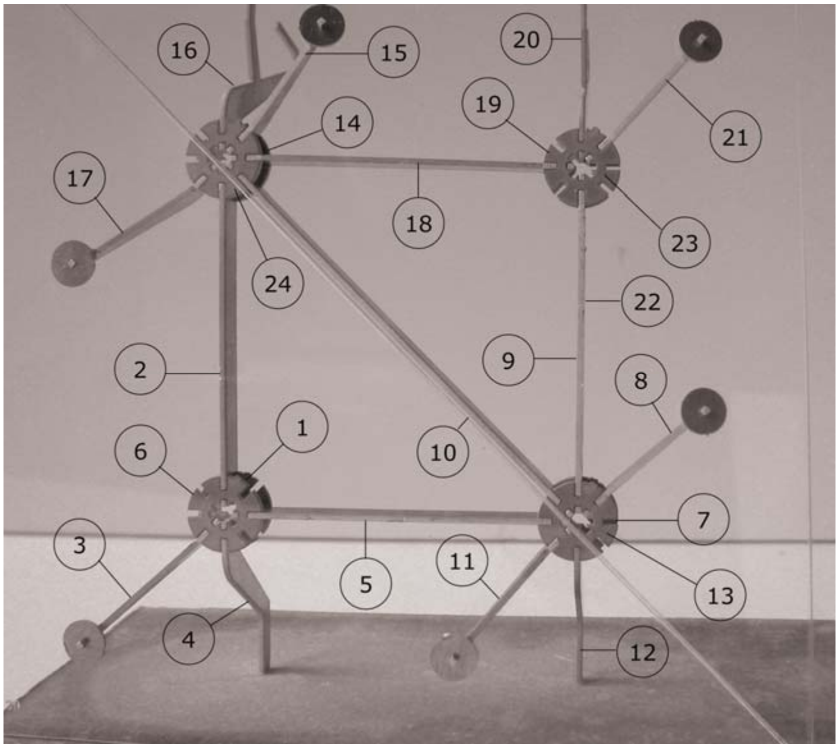
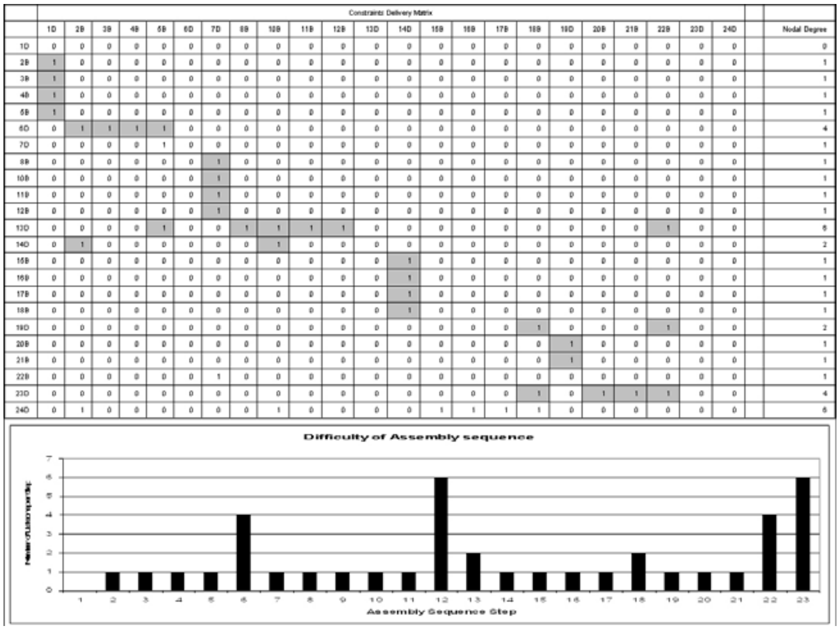


Figure 5. The assembled façade panel

A representation of the assembly with the liaison graph shows that while the assembly is possible, there are two steps in the assembly sequence of high difficulty because they need simultaneous connections. The nodal degree distribution along the actual assembly sequence shows the difficulty of each step as a function of the number of connections that have to be achieved with the rest of the assembled artifact. The nodal degree sequence is then inserted as input in the simple System Dynamics model that represents the assembling process. The model clearly shows that assembling rate will significantly drop at the 12th and 23rd step of the assembly sequence.



Constraints Delivery Matrix

	1D	2B	3B	4B	5B	6D	7D	8B	10B	11B	12B	13D	14D	15B	16B	17B	18B	19D	20B	21B	22B	23D	24D		Nodal Degree
1D	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0
2B	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		1
3B	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		1
4B	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		1
5B	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		1
6D	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		4
7D	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		1
8B	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		1
10B	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		1
11B	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		1
12B	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		1
13D	0	0	0	0	1	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	1	0	0		6
14D	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0		2
15B	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0		1
16B	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0		1
17B	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0		1
18B	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0		1
19D	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0		2
20B	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0		1
21B	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0		1
22B	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		1
23D	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	1	1	0	0		4
24D	0	1	0	0	0	0	0	0	1	0	0	0	0	1	1	1	1	0	0	0	0	0	0		6

Figure 6. Assembly sequence matrix and degree distribution

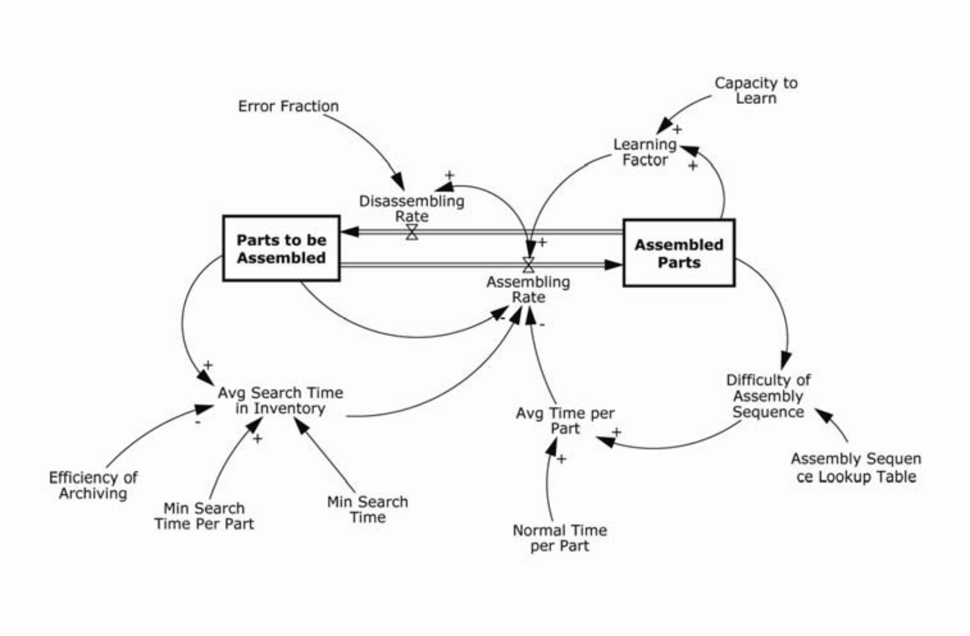


Figure 7. System Dynamics model of assembly process

5. Results

The presented method was successful in revealing information that cannot otherwise be studied with typical digital modeling techniques. This information has to do with modeling of processes rather than modeling of forms. Points in the process of high risk were located and they would be valuable if the designers followed this methodology during design. Another benefit of the approach is the high level of abstraction; network based modeling and System Dynamics modeling can take place during design development without requiring detailed geometric information. This is significant information during design development in the digital value chain.

6. Discussion

This paper showed and explained why the role of design has changed in the digital value chain. It illustrated problems that designers face by demonstrating examples. The paper moreover suggested a systemic direction for designers to evaluate design processes from the perspective of the value chain. The method however only indicates a direction and it by no means constitutes a panacea. Unless designers realize their new role, they will be disconnected and removed from authority from the digital value chain. This paper concludes by encouraging designers to explore tools from systems theory and integrate them in design development to better frame and understand problems of digital design for production.

7. Bibliography

Bertalanffy, Ludwig Von. *General System Theory: Foundations, Development, Applications*. George Braziller, 1976.

Dori, Dov. *Object-Process Methodology*. Springer, 2002.

Forrester, Jay Wright. *Industrial Dynamics*. Pegasus Communications, 1961.

Forrester, Jay Wright. *Principles of Systems*. Pegasus Communications, 1968.

Newman E. J. Mark. "The structure and function of complex networks." *SIAM Review* vol. 45 (2003): 167-256

Mitchell, W.J. & McCullough, M., 1995. *Digital Design Media* 2nd ed., Van Nostrand Reinhold.

Ohno, Taiichi. *Toyota Production System: Beyond Large-Scale Production*. Productivity Press, 1988.

Porter, Michael E. *Competitive Advantage: Creating and Sustaining Superior Performance*. Free Press, 1998.

Sass, Lawrence, Dennis Michaud, Daniel Cardoso. "Materializing a Design with Plywood", *ECAADE*, Frankfurt, Germany, Sept. 2007.

Schodek, Daniel, Martin Bechthold, James Kimo Griggs, Kenneth Kao, and Marco Steinberg. *Digital Design and Manufacturing: CAD/CAM Applications in Architecture and Design*. Wiley, 2004.

Shannon, Claude E, Warren Weaver, and Shannon. *The Mathematical Theory of Communication*. University of Illinois Press, 1998.

Simon, Herbert A. *The Sciences of the Artificial - 3rd Edition*. The MIT Press, 1996.

Steward, Donald V. *Systems Analysis and Management: Structure, Strategy and Design*. Petrocelli Books, 1981.

Whitney, Daniel E. *Mechanical Assemblies: Their Design, Manufacture, and Role in Product Development*. Oxford University Press, USA, 2004.

Womack, James P., and Daniel T. Jones. *LEAN THINKING : Banish Waste and Create Wealth in Your Corporation*. Simon & Schuster, 1996.

8. Acknowledgements

The first experiment (design, fabrication and assembly of a chair) is a team project in class *4.580: Inquiry into Computation and Design* (Prof Terry Knight, Prof Lawrence Sass), Massachusetts Institute of Technology, fall 2006. Team members: Joshua Lobel, Magdalini Pantazi, Dimitris Papanikolaou.

The second experiment (design, fabrication, and assembly of a mockup of a façade panel) is an individual project in class *4.592 Special Problems in Digital Fabrication* (Prof Lawrence Sass), Massachusetts Institute of Technology, Spring 2007. Team member: Dimitris Papanikolaou.

All figures are property of the author.