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A FUNCTIONAL PERSPECTIVE ON THE EMERGENCE OF DOMINANT DESIGNS

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ABSTRACT

Models of long-term product innovation depict the trajectory of products through an evolutionary selection metaphor in which product designs converge toward a dominant design. The product innovation literature favors trajectory descriptions based on the physical manifestations of products while neglecting to account for solution principles. This paper offers a new way to explain the life-cycle of product innovation through the identification of motifs that describe the functions of a product. Functional motifs are recurrent function blocks across multiple generations of designs for a product. A collection of functional motifs defines the functional architecture of the product. Using some key examples from innovations in sewing machines, the paper illustrates the occurrence of motifs as the basis for detecting the emergence of a dominant design. Patents related to the sewing machine over 177 years are analyzed to identify functional motifs characterizing the evolution and convergence toward a dominant design. Results show that motifs do not change over long periods once a dominant design emerges even though components continue to change. This observation confirms a view of dominant designs as a technological frame but refutes the notion that design no longer matters in the era of incremental change. These motifs refine our understanding of how designs evolve along a particular path over the course of product innovation.

Keywords: functional reasoning, machine theory, product design

1. INTRODUCTION

Numerous studies assume, investigate, or develop the idea that products improve over time by following prescribed patterns. Evolutionary models depict products as evolving through an evolutionary process of variation, selection, and retention [1]. Viewed in this evolutionary perspective, product improvements over time are seen as defying systematic modeling because they follow idiosyncratic or random processes with a path-dependent trajectory determined by the resources created by a specific technological development [2]. One way path dependency manifests is in the physical architecture of the product. For example, the evolution of commercial jetliners can be described by the change in the location and number of engines to the (current) dominant design of one engine mounted underneath the wings. Once a company commits a specific product architecture, only at high cost and with rarity does a company change the physical architecture of a product [3].

Therefore, scholars typically describe the long-term evolutionary improvement of a design through a description of changes to its physical architecture. Fujimoto [4] concluded from observations of the automotive industry that, “In order to effectively analyze and compare the industries of this century, . . . we must continue to carefully investigate the design attributes of our artifacts, including their architecture” [4, p. 15]. The unit of analysis of an architecture is typically the entire product or the subsystem [5]. This physical architecture perspective has become the accepted way to understand the trajectory of product improvements over time. Many researchers verify the stability of a dominant design based on observations of the physical architecture. The complexity of a product architecture [6] can cause solution principles to endure and become increasingly entrenched due to the cost of change. The maturity of technologies embodied in key components of a product creates an upper limit on a product’s overall improvement potential [7].

Our own research has suggested that a focus on the physical architecture can obscure the effect of the functional architecture on creating path dependency in product improvement over time. In other words, the choice of a particular combination of functions—as opposed to components—and the architecture of those functions will create a path dependency that *precedes* the component design and product architecture. The complexity of a functional architecture [8] creates technological lock-in due to the cost of changing a functional architecture even if the physical product architecture remains modular and amenable to change. The hypothesis is that a functional architecture and its expression in a physical architecture, which together make up a product’s solution principles, influence product evolution. Over time, the interplay between a product's functional and physical architectures may produce specific characteristic patterns of product evolution that will not be evident from a study of the physical architecture alone.

Identifying the structures of solution principles having improvement-enabling or improvement-curtailing properties can refine our understanding of why products evolve along a particular path throughout the life cycle. As a start, this paper focuses on motifs associated with the functional architecture of a product. The method of motif identification should apply to solution principles as well, but the focus on functional architectures is intended to prevent the complexity of physical architectures from masking the central role of functional choices in shaping the trajectory of product improvement over time.

To illustrate the identification of motifs, this paper will study the evolution of the sewing machine. The following section provides the theoretical background underpinning the choice of functional architecture as the means to detect the emergence of a dominant design. Based on the theory, the paper explains the method for identifying functional motifs. This method is illustrated through the analysis of the product innovation trajectory of the sewing machine from the periods 1845–1880 and 1900–2022.

2. BACKGROUND

The classic model of product innovation by Abernathy and Utterback [9] hypothesizes that a new product is introduced into the market when a scientific breakthrough or significant performance improvement occurs. Multiple competing designs for this new product will emerge as firms test different groups of solution principles to match product performance and cost better with customer preferences. That is, firms (initially) compete on product differentiation. Eventually, the industry settles on a dominant design encompassing an industry's selection of constituent technologies embodied by the physical architecture. Social, political, and organizational dynamics drive firms' decisions to select and converge on a dominant design [1]. Once a dominant design emerges, the basis of competition shifts. Companies compete on production process efficiency rather than performance or even the "design" of the product *per se*.

Many scholars have argued that this reliance on the physical architecture of a product to exemplify a dominant design needs to consider the coalescing of technological principles that precede the selection of components and their configuration into a product. The idea that dominant designs represent a convergence of solution principles and not simply a particular assemblage of technologies was theorized by Kaplan and Tripsas [10]. Kaplan and Tripsas [10] introduced the concept of technological frames to encompass the (technical and market-oriented) knowledge underpinning products and the embodiment of that knowledge in the physical realization of the product. This theorizing departed from the prevailing view in industrial and organizational economics that economic or organizational factors such as demand and technical competence drive the emergence of dominant designs.

This research builds on the concept of using technological frames to analyze the trajectory of the design of a product. The research leverages the concept of functional models to represent a technological frame. Goel [11] equates functions with technical frames, stating that functions are "mental abstractions that enable hierarchical decomposition of a complex system into subsystems" [11, p. 204]. Functions are central to defining a technical system because they characterize the reasoning associated with a technical system, from its goal to its structure [12]. Functional models represent designers' knowledge about the technical systems they design [13]. These functional models can take different forms [14], including hierarchical descriptions of the flow of material, energy, or information through the system [15] and how the flows are transformed. They can also include the human and technical processes that work together to achieve a specific outcome. In this research, functions refer to an abstraction of applied physics principles that a designer has intentionally selected and assembled to act on a set of inputs to produce a desired output. Functions capture the knowledge a designer must have to build a technical system that works on the physical world in a desired way.

This paper will explore the idea that changes in a functional architecture represent a convergence of solution principles in the trajectory of a product's design over time by analyzing the functional architecture of the sewing machine. Centuries of tinkering and experimentation with the manual process of combining thread and cloth with a needle preceded the sewing machine's historical development. By 1790 Thomas Saint of Britain was issued patent 1,764 for a device characterized as the world's first sewing machine design. However, this characterization did not happen until the late 19th century, and thus the invention likely did not play a significant role in the further development of sewing machines. Nevertheless, manufacturing improvements such as low-cost cast iron, novel fabric weaving techniques, and increasing demand for manufactured textile goods spurred many inventions about the sewing machine. American and British inventors continued to produce clever and interesting designs throughout the 1800s as the basic functional architecture emerged [16]. According to the classic technology life-cycle model, this period of the early 1800s represented the era of ferment. By 1851, the basic functional architecture was established, and the first commercially successful sewing machines had been patented. The definitive history book *The Sewing Machine: Its Invention and Development* [16, p. 19] summarizes six elements of the functional architecture associated with the first commercially successful sewing machines (with emphasis added to highlight the essential functions):

> The requirements for producing a successful, practical sewing machine were: a **support for the cloth**, a needle to **carry the thread through the fabric** and a combining device to **form the stitch**, a feeding mechanism to **permit one stitch to follow another**, tension controls to **provide an even delivery of thread**, and the related mechanism to **insure the precise performance** of each operation in its proper sequence.

These six 'functions'—carry thread, form stitch, permit one stitch after another, provide thread delivery, and ensure precision—form the basis of sewing machine innovation throughout the last 180 years. As the passage implies, it was an assemblage of specific *functions* that defined a working sewing machine, not the physical architecture itself. Inventors toyed with this functional architecture to produce thousands of designs, some of which align closely with a dominant functional architecture, and others that diverged with more radical functional architectures. As such, the history of the sewing machine provides an interesting case to test the idea that functional architectures can better depict the trajectory of change when changes (or lack of changes) to the physical architecture create ambiguity in knowing when a product is evolving from one era to another.

Section 3 describes the approach taken to identify functional motifs across multiple generations of sewing machines and the patent selection process used to obtain technical data on those sewing machines. In Section 4, we describe the motifs identified in the sewing machines and discuss their use in understanding design trajectories. Section 5 offers concluding remarks on how this work updates theories about product evolution and the importance of focusing on functional architectures in the prediction of product evolution.

3. METHODS

A technology life cycle takes place over decades. Therefore, The case method is appropriate for observing an innovation's emergence and stabilization [17]. We derived cases (technical design data) for sewing machine design innovations from patents for sewing machines. The US Patent and Trademark Office (USPTO) has granted thousands of patents to innovations associated with the sewing machine over the past 200 years since the first machines were built. While it could be possible to create a functional model for each innovation patented, our intent for this analysis is to sample the sewing machines that have been designed and commercialized to determine whether changes at the functional level are occurring or have largely ceased.

We identified functional changes in sewing machines in three phases, conducted in iterations as patterns emerged in the data to guide more effective patent searches. The purpose of the first phase was to identify sewing machine patents relevant to the research goals. The book *The Sewing Machine: Its Invention and Development* [16] provided a list of crucial early sewing machine patents. Then, using code written in *R*, we generated a list of terms relating to frequently patented sewing machine innovations. We used these terms to search the US patent database, resulting in a compilation of patents for each innovation from 1900 to the present day. In the second phase, we created function decomposition models (functional models) of each patent using existing functional decomposition methods adapted to sewing machines. In the third phase, we measured functional changes between different generations of sewing machines and their respective functional models using graph edit distance to identify functional motifs. Finally, we contrasted the measured functional changes with observable changes to the physical architecture.

3.1 Phase 1: Patent Selection

We aimed to identify patents that show successive improvements in physical and functional architecture. These are divided into two groups. The first group consists of early and important sewing machine patents from the middle of the 19th century. The second group consists of sewing machine patents from 1900 to the present.

The selection of patents in the first group is intended to enable observation of the era of ferment—the period when sewing machine manufacturers were proposing various functional approaches to a successful sewing machine, and the industry had not yet settled on a dominant design. For the period up to the 19th century, the researchers turned to the book *The Sewing Machine: Its Invention and Development* [16] by Grace Rogers Coopers. This book is widely considered the definitive text on the history of the sewing machine. The book identifies twelve patents that defined early US sewing machine designs, including four patents preceding the first commercially successful machine and eight patents developing essential elements of a sewing machine. Table 1 summarizes these patents. We chose additional patents from a set of manufacturers described in this book who have substantially more patents (7 or more, based upon a frequency analysis of the number of patents assigned to various inventors) than other inventors. There are six such inventors: W. B. Bartram (7 patents), David W. Clark (8 patents), James E. A. Gibbs (7 patents), James S. McCurdy (8 patents), Isaac M. Singer (9 patents), and Charles H. Wilcox (7 patents) [16].

TABLE 1: SIGNIFICANT EARLY US SEWING MACHINE PATENTS

Patent Number	Author	Year
2,466	Greenough	1842
2,982	Bean	1843
3,389	Corliss	1843
3,672	Rogers	1844
4,750	Howe	1846
6,099	Morey/Johnson	1849
6,439	Bachelder	1849
6,766	Blodgett/Lerow	1849
7,776	Wilson	1850
8,294	Singer	1851
8,296	Wilson	1851
9,041	Wilson	1852
12,116	Wilson	1854

The analysis of the modern (1900 onward) patents is intended to observe the era of incremental change. Patent selection for this period does not rely on historical records and can be partially automated due to the availability of digitized patent data. First, all US patents having the exact phrase "sewing machine" in the title were downloaded from the Google Patents database. The patent titles were analyzed using a natural language algorithm and clustering analysis in *R* to identify interesting and frequent phrases, or innovations, in the titles. These phrases ended up relating to components implementing key functions in a sewing machine, such as the presser foot or the needle bar. This produced a list of 12 innovations relating to sewing machines and associated with high patent activity. A given innovation, along with the phrase "sewing machine", was used to search the Google Patents database again along with the following criteria:

1. Patent Office: US

2. Language: English
3. Status: Granted
4. Type: Patent
5. Publication date: 1900 to present day
6. Excluded terms: hat, shoe, book, button, safety, industrial

This was repeated for each innovation generating 12 separate lists of patents from 1900 to the present. From each list, the researchers selected at least one patent within each quarter century between 1900 and 2025, as well as highly cited patents. This process identified 106 patents.

In total, 164 patents were identified during patent selection. All of the patent abstracts were read to determine the extent of the innovations (patent claims). We were interested in identifying patents that made claims to new functions (Later, in the section on graph edit distance, new functions are tantamount to a new function block.) or new ways of achieving existing functions (considered in the graph edit distance as a substitution of one or more function blocks) rather than enhancements to existing functions. Ninety-seven (97) patents were excluded from further analysis, resulting in 67 total functional models (33 machines from the era of ferment and 34 newer machines from the era of incremental change) analyzed. These exclusions occurred for various reasons:

1. The patent showed no functional difference from other patents. In other words, it was likely that we had reached saturation in the sampling of patents to observe functional change. Additional patents would not yield new information. Instead, the patent claimed performance improvement through design modifications to one or more components. The functional model for the machine described in the patent could be assumed to match that of an already existing model. Subsystem patents in particular often showed complex assemblies, but a review of the patent abstract and core functions revealed that the patent yielded no new functionality.

2. More patents in the modern era were identified as interesting than could feasibly be modeled due to the complexity of the functions described in the patent. Future work will reexamine these patents to determine whether they need to be modeled.

The researchers are also in possession of a Husqvarna Viking 950, a complete sewing machine released in the 1980s. Analysis of this machine will assess the functional difference between early patent designs and a complete sewing machine that demonstrates an integration of relatively modern solution principles.

3.2 Phase 2: Functional Modeling

In the second phase, the mechanical design of sewing machines and their subsystems, as described in patents, was represented as a functional model. Functional modelling is a well-established method for abstracting a physical product or system to its functional architecture in which the goal is to describe the design intent in functional terms. Functional modeling aims to formalize the language (usually through an ontology) and the process by which the structure of a product's functions is defined. Functional models typically consist of a flowchart, or graph, with nodes representing functions and edges representing flows.

Generating functional models is largely a manual process. Some common challenges and critiques of functional modeling focus on the subjective nature of the method [12, 13]. We investigated automated techniques [18] but decided that none were able to integrate the analysis of pictorial and linguistic descriptions of mechanical devices to determine their primary function. Functions are characterized by an ensemble of components, design principles, and designer intent, the totality of which is—at present—only understandable through human expertise and intuition. The steps outlined in the rest of this section are taken to address this uncertainty through training and duplication.

The ontology for functional modeling in this research is based on the functional basis [15, 19]. The functional basis explicitly defines a set of functions and flows that encompass possible functionality in mechanical systems. Stone calls for modeling the most "elemental" functions in a design [15]. Common functions in a sewing machine are "secure", "regulate", and "change", and flows may be energy (usually human, mechanical, or electrical energy), material (i.e., the fabric and the thread), or signal. In this paper, we name the instance of a function and its inflows and outflows as a *function block*. This broad guidance for functional modeling results in variable approaches to functional modeling styles, which illustrates the under-defined nature of the functional modeling [14]. For this project, it was critical to model patents in a way that is consistent and form-agnostic. This was achieved by using established modifications to the function list, expanding the definitions of certain project-specific functions, and framing the functional analysis through a lens of "design-intent".

The format of patents aided in the understanding of design intent. All patents are presented as a detailed written description augmented by figures at varying levels of detail. While form may be best understood from an examination of the figures, design intent can be understood through the written description, provided the inventor was sufficiently clear about their intentions. The functional model therefore most closely follows the written description. Conversely, if the written description excludes a certain design decision or component, it was important to not "fill in" that gap in the functional model.

The researchers relied on several additional clarifications of the functional basis to improve the reliability and repeatability of the functional modeling.

1. The state of the art provides that functional decomposition is most accurate and useful when functions and flows are limited to the "second level" of the functional basis [20].

2. Approaching "form-agnostic" in the modeling process begins by eliminating any indication of form within each function. Also, *groups* of functions must not indicate design form. This comes from "over-modeling" the design by assigning a function to individual components rather than considering the broader design intent of an assembly of components.

3. Since functional modeling is based upon natural language instead of algorithmic definitions, and the relationship between components and their function(s) are usually specified

in the patent text, certain components could be named by the functions they accomplish. As well, these components recur across many machines; therefore, maintaining a list of common components and their functions increases the repeatability of functional modeling across machines. Table 2 lists common component assemblies and the functions they implement.

TABLE 2: EXAMPLES OF COMMON SEWING MACHINE COMPONENT-FUNCTION CORRELATIONS

Mechanism	Function Block
Cam mechanism	Change ME
Scotch yoke	Change ME
Reducing gear mechanism	Change ME
Needle (any type)	Transfer ME (to Thread 1)
Rotary hook	Transfer ME (to Thread 2)
Vibrating Shuttle	Transfer ME (to Thread 2)
Feed-wheel	Transfer ME (to Cloth)
Static presser-foot	Secure Cloth
Reciprocating presser-foot	Stabilize Cloth
Thread length control device	Regulate ME
Thread tensioner	Regulate Thread (1 or 2)
Driveshaft to multiple outputs	Distribute ME

Figure 1 illustrates an example of the functional analysis for a sewing machine patent. This example pertains to a group of functions related to the flow of mechanical energy (ME) to the cloth feed wheel in patent 8,294, a motif documented in many patents. The functions are Change ME → Regulate ME → Transfer ME. The figure shows the progression of patent interpretation. First, reading the entire written text yields information about the context and purpose of the design (**A**). Then the reader should follow along the progression of component descriptions in the text while also reading the figures to build a mental model of the structure of the design (**B**). Readers are encouraged to take notes at this stage. Next, the reader should return to the text to clarify assumptions about the functionality that might be implied by the figure. This critical step ensures that the functional model only models information described in the text so as to align the model with the designer's intent. Finally, the reader should construct the functional model (**C**). This is an iterative process that requires several back-and-forth passes through the patent to continue to clarify assumptions about the functionality. Often a component or subsystem has multiple functions, and the reader should identify and include only the primary functions, rather than all possible functions.

Fourteen (14) undergraduate research assistants (URAs) were trained on the functional decomposition process for sewing machine patents. All of the URAs had taken the junior-level mechanical design course, which teaches functional modeling, and the mechanical component design course. They had received a grade of B or higher in both of these courses. The URAs were trained on the architecture (including subsystems and their components), operation (how to sew), and the functionality (functional elements of a successful sewing machine) of sewing machines. For example, they were shown the presser foot and explained its function according to the functional basis. How this information is presented in the language of patents was also shown. Each patent was read in full by each URA. Two URAs each independently created a functional model of the patent. Then the URAs compared models and discussed and resolved discrepancies. Unresolvable discrepancies were discussed with a member of the research team (an author) to reach a consensus. Finally, each model was reviewed for accuracy by a member of the research team.

3.3 Phase 3: Analysis and Finding Functional Motifs

The analysis aims to identify motifs in the data by comparing each patent's functional and physical architectures. Robust analysis tools for functional models are unavailable or only apply to a particular device. Therefore, the researchers took a general search approach to identify motifs in the data. Specific methods used include visual comparisons of functional models assisted by measures of graph edit distance (GED) to identify the degree of change between pairs of functional models.

To find the motifs, the researchers followed an established procedure [21] to identify recurrent sub-graphs and the criteria for ascribing a recurrent pattern as a motif. A motif-finding algorithm searches the adjacency matrix of a network for all nodes connected to an initial node up to an n-node subgraph. We adapted this technique to identify motifs qualitatively. The process begins by identifying a function block and its inflows and outflows. This function block is usually associated with a subsystem that implements one of the critical functions of a successful sewing machine. Then, we successively increase the subgraph into a 2-node subgraph, 3-node subgraph, etc., until we find the largest subgraph that contains matching function blocks repeated across multiple patents. The largest set (n-node subgraph) of recurrent function blocks is a motif. Motifs for each element of a successful sewing machine concatenate to produce a functional model of the *dominant functional architecture*.

Functional models were then compared to the dominant architecture to determine the degree of alignment. We used visual comparisons to identify isomorphic subgraphs and graph edit distance (GED). Graph edit distance was implemented as a metric of difference between pairs of functional models. Functional models are graphs with nodes (functions) and edges (flows). Prior research in vector and network-based measures of product similarity recommended that the GED is an appropriate metric when the products are of similar complexity and are not expected to be highly dissimilar [22]. The GED [23] is the sequence of operations that transform a source graph into a target graph. A GED algorithm calculates the minimal set of operations that can transform a graph representation from a source model to a target model. Graph edit transformations consist of three operators: node insertion or deletion, edge insertion or deletion, and node or edge substitution. Each operation (node addition, deletion, or substitution) is a single transformation. A node addition is tantamount to the addition of a function; a node deletion is tantamount to the deletion of a function. A node substitution is regarded as achieving the same design intent in a new way. The total transformation is the sum of all the operations in the sequence. Several feasible sequences are possible to transform a source graph into the target graph. GED is reported as the fewest transformations.

We use the NetworkX [24] Python module to calculate an exact GED between functional models. graph_edit_distance(G1, G2) [25] takes two graph data structures (directed or undirected) as its arguments and calculates the number of edits (including label renaming, node deletion/creation, and edge deletion/creation) required to change one graph data structure to another.

4. RESULTS AND DISCUSSION

This section presents the results of the methods, including examples of observed functional motifs and how the motifs relate to historical context. The methods identified a variety of motifs in early sewing machine functional models. Some motifs are found in most functional architectures, while others are only associated with historically significant or commercially successful machines. Additionally, certain motifs are associated with frequently patented subsystem solution principles. Graph edit distance supports the emergence of a dominant functional architecture (DFA). The results show that a DFA emerges early in the development of sewing machine design, and that continued invention competes on solution principles within the dominant functional motifs. Machines implementing the DFA are found to show minor variations in their functional architecture, which can largely be attributed to increased control and the effect of electrification.

4.1 The Dominant Functional Architecture

The dominant functional architecture of sewing machines is characterized by an assembly of five functional motifs, seen in Fig. 2. Per the method described in section 3.3, the motifs are the largest repeating subgraphs across most patents (in other words, across multiple generations for the design of a sewing machine). These motifs appear frequently either on their own or alongside other motifs in sewing machine functional architectures. In the figure, motifs are linked together in a unified architecture because input and output energy and material flows align (and the motifs are frequently grouped this way). This architecture has a distinct visual modularity, consisting of three branches for each of the needle thread, the cloth, and the bobbin thread (motifs 2, 3, and 4), sandwiched between motifs 1 and 5.

The motifs are delineated in Fig. 2 by dashed borders. Motif 1 on the left side consists of the division ("distribute") of mechanical energy into three branches, then conditioning ("change") of that energy. Mechanical energy is the only flow in and out of this motif. The 5^{th} motif on the right side is the convergence of material and mechanical energy flows into a single "couple solids" block, representing the complex motion of bringing together the two threads and cloth into a stitch. This motif also shows the stitched cloth and mechanical energy leaving the system. The motifs for the needle and bobbin thread (2,4) are identical except for the difference in material. They consist of the import of thread and the transfer of mechanical energy to the thread to move and guide it through the system. Additionally, a control signal for thread tension goes to a regulate block. The motif for the cloth (3) is similar to 2 and 4 with the addition of a "secure cloth" function. The regulate block in this motif represents the ability to control the direction of cloth movement. The in and out flows for these three motifs are a single flow of mechanical energy and the respective material.

While patents increasingly align with the DFA into the 20^{th} century, we noticed one constant change. Fig. 3 graphs the number of signal flows in functional models of early patents between 1842 and 1868. While there are very few control signals early in the design evolution of the sewing machine, after the emergence of a DFA the number of control signals increases. This finding shows that after the era of ferment, design competition shifts to the design of components that implement functions to

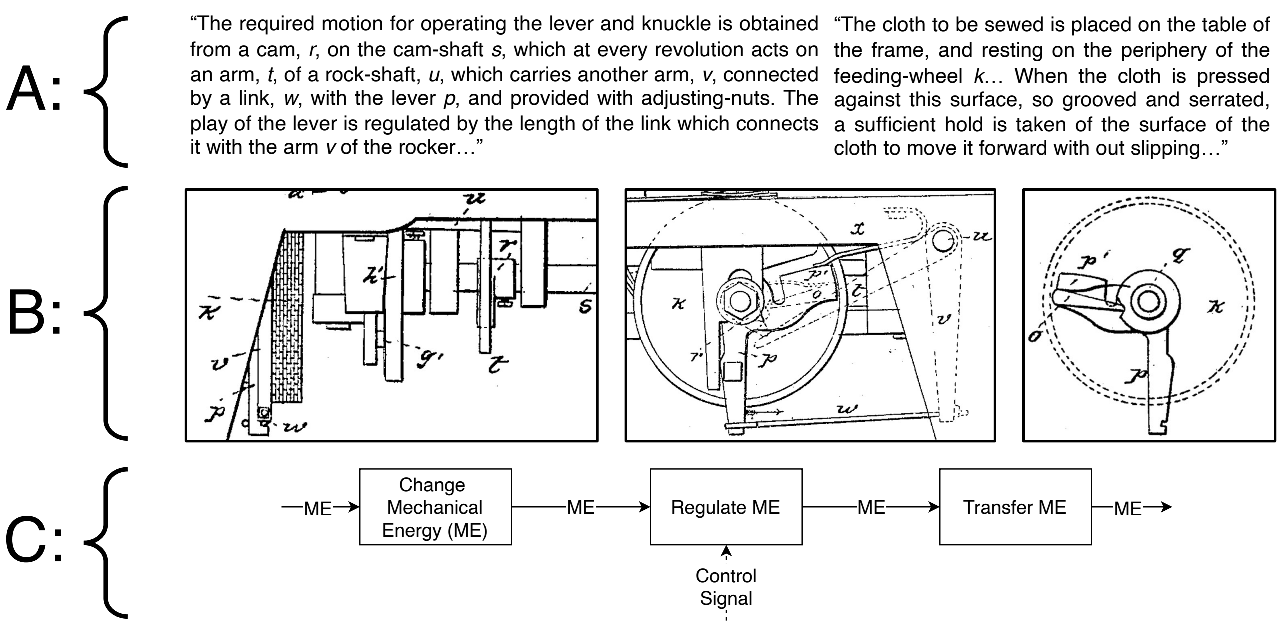

FIGURE 1: METHODOLOGICAL DEMONSTRATION OF FUNCTIONAL ANALYSIS OF SEWING MACHINE PATENT 8,294

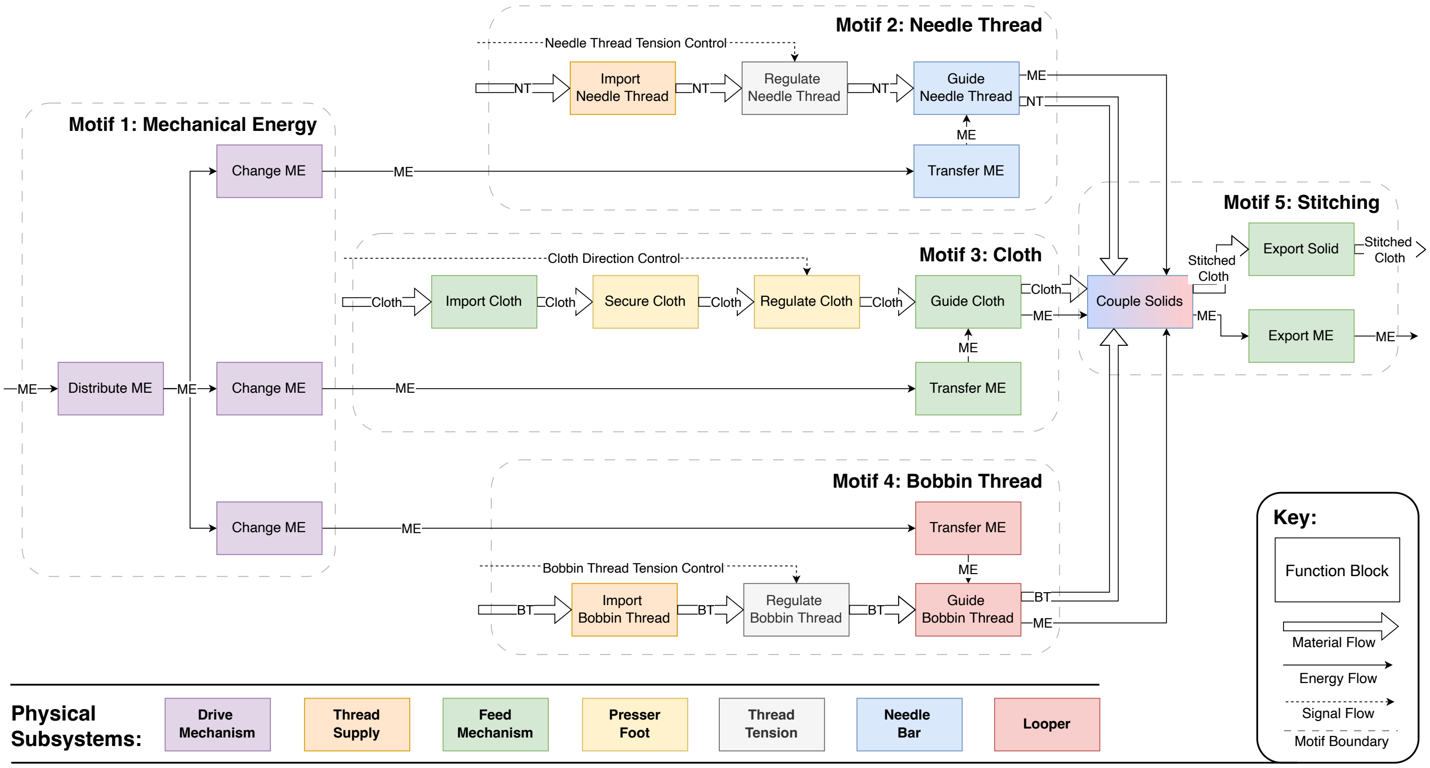

FIGURE 2: SEWING MACHINE DOMINANT FUNCTIONAL ARCHITECTURE AND SUBSYSTEM MAPPING

increase precise control. If firms are saving manufacturing costs during the era of a dominant design, they are likely investing the manufacturing cost savings into the design of new control subsystems.

Color coding in Fig. 2 represents the relation between functions and physical subsystems in the basic design of a sewing machine. The seven subsystems are derived from the list of innovations described in Section 3.1, and thus are terms corresponding to significant patent activity in the 20th and 21st centuries. Functional models of patents from the innovations fit within the DFA and generally align very closely with it. As with early machines, differences between patents – especially relating to performance, reliability, or usability – do not necessarily result in differences between their functional models. Significant change does occur, however, concerning control signals and regulate blocks. Just as in early machines, a significant change occurred as inventors found new ways to add finer control.

The functional models were compared based on GED. Fig. 4 shows the GED between the dominant functional architecture and seven essential sewing machine functional models. The GED is calculated with both with the complete functional models (blue line) and with all control signals and "regulate" blocks removed (orange line). Control signals are important but do not usually result from more profound functional architecture differences between two models. Removing them reduces "noise" in the comparison and shows how much of an impact control signals have on specific machines, such as the modern machine.

While the graph edit distance helped gauge the degree of change in functional models, the researchers determined that even the GED did not have sufficient resolution to determine the functional changes precisely. The GED has no mechanism to account for the importance of change between two graphs because, in the absence of empirical data, the GED treats the cost of all changes (node/edge deletion, addition, or substitution) equally. GED should, therefore, only be taken as a preliminary indication of the degree of change. Some functional changes may have greater significance or represent a fundamental restructuring of the interpretation of the dominant architecture. For example, substituting functions would be a more significant change from an engineering perspective. However, the substitution change would appear identical to the simple addition of a control signal when viewed from the perspective of GED.

Patent 4,750 was the first to demonstrate alignment with most of the dominant functional architecture, perfectly aligning with four of the motifs and near aligning with the other two. The graph edit distance between the DFA and patent 4,750 is low at 27 transformations (if including signal blocks). Figure 5 shows the functional model of the modern sewing machine, with highlighted blocks that match up with blocks in patent 4,750. There is a significant carryover from patent 4,750, despite 131 years between their invention. The functional architecture of the modern machine shows distinct similarity with those of early sewing machines, demonstrating the endurance of the dominant design. One reason for the differences in modern machines compared to early ones is electrification. Electrification enables greater control and more accurate interaction with the machine, leading

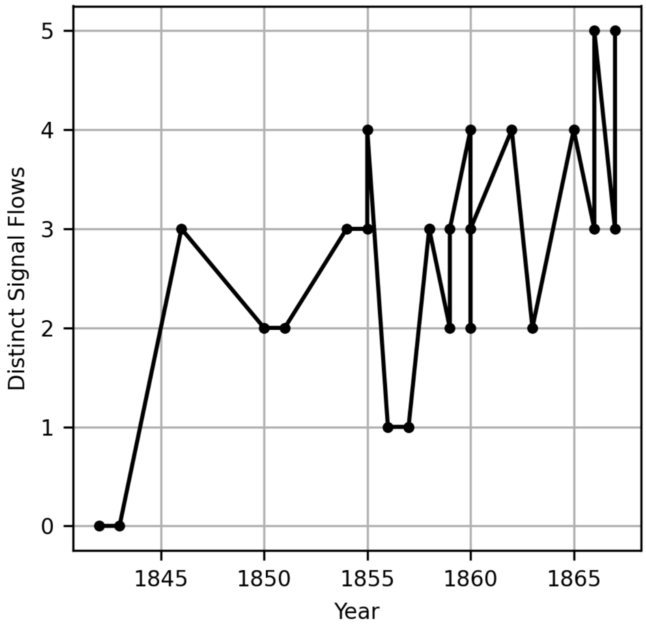

FIGURE 3: NUMBER OF SIGNAL FLOWS IN FUNCTIONAL MODELS OVER TIME

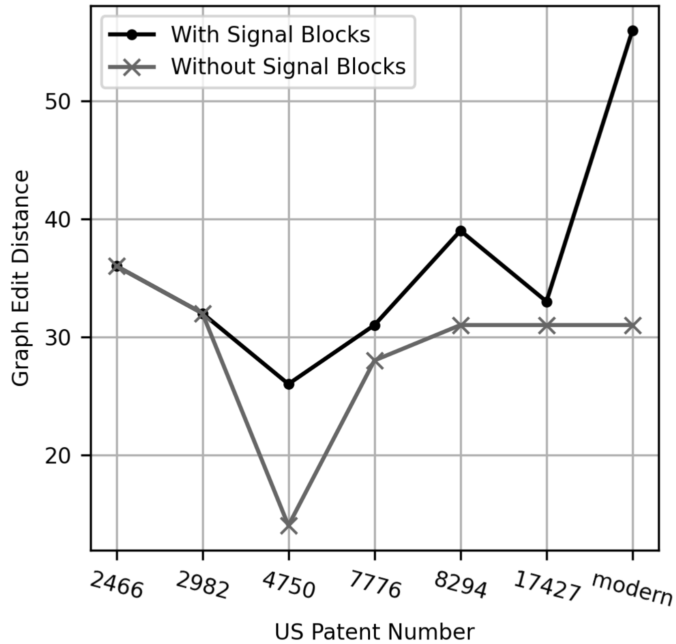

FIGURE 4: GRAPH EDIT DISTANCE FROM DOMINANT FUNCTIONAL ARCHITECTURE

to the addition of "control" signals and "regulate" blocks in the functional model. Historically, patent 4,750 has had an outsize impact on future patents and is foundational to sewing machine design for decades after its issuance. While inventors continued experimenting with divergent functional architectures well into the 1870s, it is clear that Elias Howe had assembled the dominant functions by 1846.

The perceived stability of the functional architecture is a result of the patent sampling process. The sampling process identified the most common phrases in sewing machine patent titles, rendering a list of patents that likely fit the dominant design. Divergent or unusual patents that break from the dominant functionality would not likely be found using this patent search process, as these unique patents would have a lower chance of relating to the most common sewing machine subsystems. Nonetheless, it is improbable that a significantly novel functional architecture emerged—and if it did emerge, it did not succeed (overtake the dominant functional architecture) because no other dominant functional architecture is observed in modern sewing machines.

4.2 Functional Stability Precedes Architectural Stability

The data show that functional stability precedes architectural stability. The era of incremental functional change began after the era of ferment in the late 19th century, yet physical architecture has continued to change dramatically. Coincidentally, physical architecture is not necessarily an accurate representation of product functional innovation. Designs with perceived differences in physical architecture may have very similar functional architectures. This phenomenon is most evident during the development of the dominant design. Both in early and newer patents, two vastly different physical architectures often have nearly identical functional models. The difference is usually negligible when comparing patents within subsystems and only marginally more significant when comparing patents of complete machines from the era of ferment.

Figure 6 shows four examples of physical implementations of the feed mechanism subsystem, aligning with the functional model shown in part C of Fig. 1. Each patent has focused on improving the design of the feed mechanism in some different way, resulting in vastly different forms. Yet the parts of their functional models relating to the feed mechanism are identical, except for differences in control and use of electricity. In some cases, electrical energy is a means to generate control signals and provide mechanical energy to the system, but these differences are external to the DFA. In particular, patent 8,850,999 (bottom right) has implemented a programmable mechanism for rotating the needle plate and feed dogs. The basic functionality—control feed direction—-existed as early as 1851.

We conclude from this observation that functional stability long preceded stability in the component architectures of sewing machines. Throughout the 1900's inventors tinkered with the assemblage of components in pursuit of increased performance, ease of use, reliability, manufacturability, and decreased cost, all while operating within the functionality established decades earlier.

4.3 New Forms of Design Competition After a Dominant Design Emerges

Conventional dominant design theory states that once a dominant design emerges, firms compete on the cost of manufacturing. This research suggests two other forms of competition. First, the results in Sections 4.1 and 4.2 demonstrate that manufacturers continue to compete on design: the design of components and

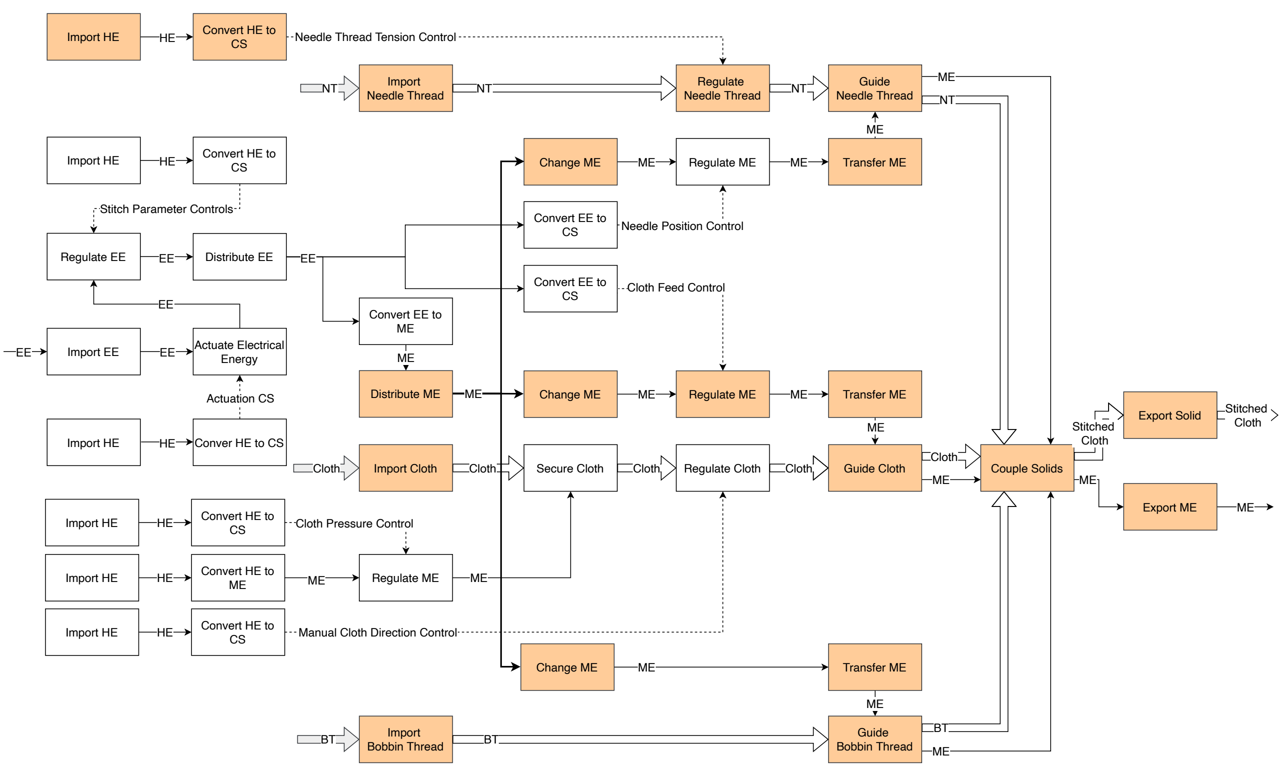

FIGURE 5: FUNCTIONAL MODEL OF MODERN SEWING MACHINE WITH HIGHLIGHTED BLOCKS MATCHING PATENT 4,750

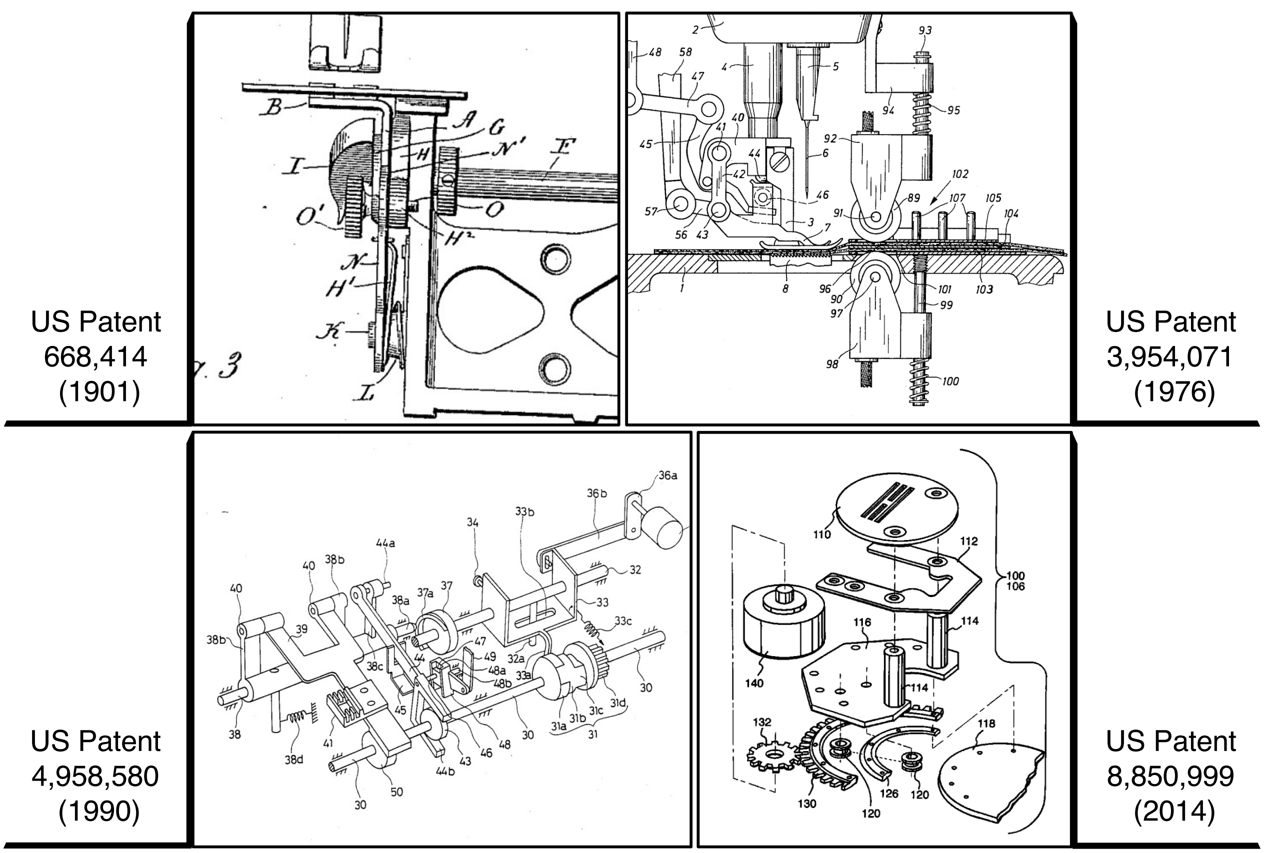

FIGURE 6: COMPARISON OF FEED MECHANISM PHYSICAL ARCHITECTURES

their configuration to increase precise control and, to a lower extent, enhancements to the design of particular components.

A second more important finding on competition is that the dominant functional architecture allows inventors to explore design solutions and functionality in sub-functions and subsystems. This design strategy is revealed in patents in the modern era. By 1900, our patent search returned markedly decreased numbers of patents for complete machines; instead, the patents addressed specific subsystems (function motifs) of the sewing machine. Before a dominant functional architecture existed, design innovations across multiple sub-functions or subsystems were riskier and more challenging because the market still needed to learn which functional architecture would result in a successful machine. During the era of ferment, we observed patents concerning entire sewing machines from 1842 (patent US 2,466) and as late as 1899 (patent US 994,532). Once the dominant functional architecture is understood by a large enough portion of the industry, invention within sub-functions is more necessary because the overall architecture is already understood. Inventors no longer have to consider and design for all functionality; instead, they only need to ensure that the sub-functions or subsystems will fit within existing architectures. Thus, the design process becomes inherently hierarchically modular.

5. CONCLUSION

This paper contributed a new approach to identifying a dominant design based upon a search for functional motifs that recur across multiple generations of a design for a product. The findings revealed that a dominant functional architecture could appear even before a dominant *physical* architecture is observed, confirming the concept of technological frames as a more suitable way to define dominant designs rather than typical approaches based on physical architecture.

A limitation of this research is insufficient data to show more completely the evolution of the sewing machine in the era of ferment before Howe's patent. Likely, many important functional ideas leading up to patent 4,750 came from non-US patents. Important early non-US [16] patents include British patents 1,764 for a machine for "stitching, quilting, or sewing", 2,769 for a machine that made the chain stitch, and 3,708, a machine for stitching together several strands of rope, and the French patent to Barthélemy Thimonnier for a machine that could produce a chain stitch using a barbed or hooked needle. These patents are available at the British Library and the France Patent Office. The researchers hope to visit these facilities to obtain digital copies of these patents and view the copy of the Thimonnier machine at the Smithsonian Institute soon.

The paper contributes to design theory in two crucial ways. First, in contrast to the design strategy recommendation that manufacturers should compete on manufacturing cost after a dominant design emerges, the findings show that manufacturers should compete on precision control. The lack of control signals appearing in the dominant functional architecture, and even during the era of ferment for the sewing machine, show an opportunity for control design to occur while design engineers resolve other functional issues. Given the low cost of microelectronic control systems, it is possible that this design strategy is already occurring in products since our data is based upon a machine invented in the 1800s. Second, the findings suggest that firms should heed and know the dominant functional architecture because they can leverage it into adjacent product categories such as shoe-sewing devices, hat-making devices, and tennis racket stringing machines. All these machines are variants of a sewing machine in the foundational functional architecture. Finally, the paper contributes to mechanical design education. Current mechanical design education practice for functional modeling is to teach students to model a single product at a time [26] and then to use the model as the basis for new designs. Teaching students about dominant functional architectures for categories of products can help them design new types of machines for adjacent purposes like it helped manufacturers in the textiles industry.

In sum, this paper introduced the concept of a dominant functional architecture by modeling multiple generations of sewing machines to identify functional motifs that converged into a dominant design. This concept contributes to the theory base for explaining a technology life cycle.

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REFERENCES

[1] Anderson, Philip and Tushman, Michael L. "Technological Discontinuities and Dominant Designs: A Cyclical Model of Technological Change." *Administrative Science Quarterly* Vol. 35 No. 4 (1990): p. 604–633.

[2] Rosenberg, Nathan. *Exploring the black box : technology, economics, and history*. Cambridge University Press, Cambridge (1994).

[3] Henderson, Rebecca M. and Clark, Kim B. "Architectural Innovation: The Reconfiguration of Existing Product Technologies and the Failure of Established Firms." *Administrative Science Quarterly* Vol. 35 No. 1 (1990): p. 9–30.

[4] Fujimoto, Takahiro. "The Long Tail of the Auto Industry Life Cycle." *Journal of Product Innovation Management* Vol. 31 No. 1 (2014): p. 8–16. DOI 10.1111/jpim.12076.

[5] Murmann, Johann Peter and Frenken, Koen. "Toward a systematic framework for research on dominant designs, technological innovations, and industrial change." *Research Policy* Vol. 35 No. 7 (2006): p. 925–952. DOI 10.1016/j.respol.2006.04.011.

[6] McNerney, James, Farmer, J. Doyne, Redner, Sidney and Trancik, Jessika E. "Role of design complexity in technology improvement." *Proceedings of the National Academy of Sciences* Vol. 108 No. 22 (2011): p. 9008–9013.

[7] Zhang, Guanglu, McAdams, Daniel A., Shankar, Venkatesh and Mohammadi Darani, Milad. "Technology Evolution

Prediction Using Lotka–Volterra Equations." *Journal of Mechanical Design* Vol. 140 No. 6 (2018): p. 061101.

[8] Dong, Andy. "Functional lock-in and the problem of design transformation." *Research in Engineering Design* Vol. 28 No. 2 (2017): p. 203–221.

[9] Abernathy, William J. and Utterback, James M. "Patterns of Industrial Innovation." *Technology Review* Vol. 80 No. 7 (1978): p. 40–47.

[10] Kaplan, Sarah and Tripsas, Mary. "Thinking about technology: Applying a cognitive lens to technical change." *Research Policy* Vol. 37 No. 5 (2008): p. 790–805. DOI 10.1016/j.respol.2008.02.002.

[11] Goel, Ashok K. "A 30-year case study and 15 principles: Implications of an artificial intelligence methodology for functional modeling." *Artificial Intelligence for Engineering Design, Analysis and Manufacturing* Vol. 27 No. 3 (2013): p. 203–215. DOI 10.1017/S0890060413000218.

[12] Vermaas, Pieter E. "The coexistence of engineering meanings of function: Four responses and their methodological implications." *Artificial Intelligence for Engineering Design, Analysis and Manufacturing* Vol. 27 No. 3 (2013): p. 191–202. DOI 10.1017/S0890060413000206.

[13] Winsor, Julian and MacCallum, Kenneth. "A review of functionality modelling in design." *The Knowledge Engineering Review* Vol. 9 No. 2 (1994): p. 163–199. DOI 10.1017/S0269888900006780.

[14] Eisenbart, Boris, Gericke, Kilian and Blessing, Luciënne. "An analysis of functional modeling approaches across disciplines." *Artificial Intelligence for Engineering Design, Analysis and Manufacturing* Vol. 27 No. 3 (2013): p. 281–289. DOI 10.1017/S0890060413000280.

[15] Stone, Robert B. and Wood, Kristin L. "Development of a Functional Basis for Design." *Journal of Mechanical Design* Vol. 122 No. 4 (2000): p. 359–370.

[16] Cooper, Grace Rogers. *The Sewing Machine: Its Invention and Development*, 2nd ed. Smithsonian Institution Press, Washington, D.C. (1976).

[17] Hargadon, Andrew B. and Douglas, Yellowlees. "When Innovations Meet Institutions: Edison and the Design of the Electric Light." *Administrative Science Quarterly* Vol. 46 No. 3 (2001): pp. 476–501.

[18] Song, Binyang, Luo, Jianxi and Wood, Kristin. "Data-driven platform design: Patent data and function network analysis." *Journal of Mechanical Design* Vol. 141 No. 2 (2019): p. 021101.

[19] Hirtz, Julie, Stone, Robert, McAdams, Daniel, Szykman, Simon and Wood, Kristin. "A functional basis for engineering design: Reconciling and evolving previous efforts." *Research in Engineering Design* Vol. 13 No. 2 (2002): p. 65–82. DOI 10.1007/s00163-001-0008-3.

[20] Sen, Chiradeep, Caldwell, Benjamin W., Summers, Joshua D. and Mocko, Gregory M. "Evaluation of the functional basis using an information theoretic approach." *AI EDAM* Vol. 24 No. Special Issue 01 (2010): p. 87–105. DOI 10.1017/S0890060409990187.

[21] Milo, R., Shen-Orr, S., Itzkovitz, S., Kashtan, N., Chklovskii, D. and Alon, U. "Network Motifs: Simple Building Blocks of Complex Networks." *Science* Vol. 298 No. 5594 (2002): p. 824–827. DOI 10.1126/science.298.5594.824.

[22] Nandy, Ananya, Dong, Andy and Goucher-Lambert, Kosa. "Evaluating Quantitative Measures for Assessing Functional Similarity in Engineering Design." *Journal of Mechanical Design* Vol. 144 No. 3 (2021): p. 031401. DOI 10.1115/1.4052302.

[23] Gao, Xinbo, Xiao, Bing, Tao, Dacheng and Li, Xuelong. "A survey of graph edit distance." *Pattern Analysis and Applications* Vol. 13 No. 1 (2010): p. 113–129. DOI 10.1007/s10044-008-0141-y.

[24] Hagberg, Aric A., Schult, Daniel A. and Swart, Pieter J. "Exploring Network Structure, Dynamics, and Function using NetworkX." Varoquaux, Gaël, Vaught, Travis and Millman, Jarrod (eds.). *Proceedings of the 7th Python in Science Conference*: pp. 11 – 15. 2008. Pasadena, CA USA.

[25] Abu-Aisheh, Zeina, Raveaux, Romain, Ramel, Jean-Yves and Martineau, Patrick. "An exact graph edit distance algorithm for solving pattern recognition problems." *4th International Conference on Pattern Recognition Applications and Methods 2015*: p. 9. Lisbon, Portugal, 2015. DOI 10.5220/0005209202710278.

[26] Nagel, Robert L., Bohm, Matt R., Linsey, Julie S. and Riggs, Marie K. "Improving Students' Functional Modeling Skills: A Modeling Approach and a Scoring Rubric." *Journal of Mechanical Design* Vol. 137 No. 5 (2015): p. 051102. DOI 10.1115/1.4029585.