Design Structure Matrix Extensions and Innovations: A Survey and New Opportunities

Tyson R. Browning

***Abstract*—The design structure matrix (DSM), also called the dependency structure matrix, has become a widely used modeling framework across many areas of research and practice. The DSM brings advantages of simplicity and conciseness in representation, and, supported by appropriate analysis, can also highlight important patterns in system architectures (design structures), such as modules and cycles. A literature review in 2001 cited about 100 DSM papers; there have been over 1000 since. Thus, it is useful to survey the latest DSM extensions and innovations to help consolidate progress and identify promising opportunities for further research. This paper surveys the DSM literature, primarily from archival journals, and organizes the developments pertaining to building, displaying, analyzing, and applying product, process, and organization DSMs. It then addresses DSM applications in other domains, as well as recent developments with domain mapping matrices (DMMs) and multidomain matrices (MDMs). Overall, DSM methods are becoming more mainstream, especially in the areas of engineering design, engineering management, management/organization science, and systems engineering. Despite significant research contributions, however, DSM awareness seems to be spreading more slowly in the realm of project management.**

***Index Terms*—Dependence structure matrix, design structure matrix (DSM), domain mapping matrix (DMM), literature survey, multidomain matrix (MDM), organization architecture, process architecture, product architecture.**

I. Introduction

MANY RESEARCHERS and practitioners have used the design structure matrix (DSM—also called the dependency structure matrix) to represent and analyze the models of complex systems. The DSM brings the advantages of simplicity and conciseness in representation, and, supported by appropriate analysis, can also highlight the important patterns in system architectures (i.e., design structures), such as modules and cycles. More recently, DSM usage has led to the development of domain mapping matrices (MDMs) and multidomain matrices (MDMs) that have broadened the capabilities and applications of the matrix-based models of complex systems and provided further insights. Such capabilities have become recognized as increasingly beneficial and important in this age of ever-more complex projects, products, processes, organizations, and other systems.

Manuscript received April 16, 2015; revised July 24, 2015 and September 16, 2015; accepted October 11, 2015. Date of publication November 20, 2015; date of current version January 18, 2016. This work was supported by the U.S. Navy, Office of Naval Research, under Grant N00014-11-1-0739. Review of this manuscript was arranged by Department Editor S. Talluri.

The author is with the Neeley School of Business, Texas Christian University, Fort Worth, TX 76129 USA (e-mail: t.browning@tcu.edu).

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Digital Object Identifier 10.1109/TEM.2015.2491283

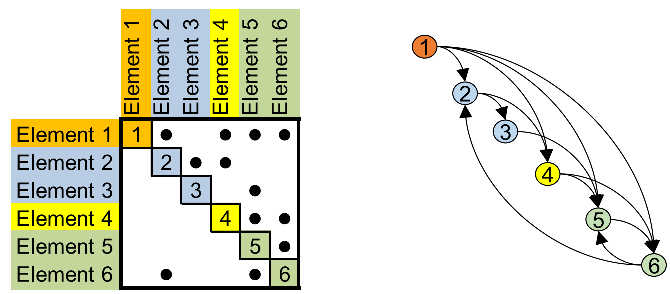

Fig. 1. Example of a binary DSM (IC convention), with optional row and column labels, and its equivalent node-link diagram (directed graph).

Steward's work on systems of equations in the early 1960s [1], [2] led to the first papers on DSM (e.g., [3]) as internal reports for general electric, but it was not until 1981 that his book [4] and paper [5] were published (the latter in these TRANSACTIONS). Aside from some citations by Warfield (e.g., [6]), few references to Steward's DSM works can be found until the late 1980s, when researchers at Massachusetts Institute of Technology (MIT), Cambridge, MA, USA, and NASA began to apply and extend the method (e.g., [7]–[9]). The 1990s saw several developments, including the broadening of DSM applications beyond Steward's temporal models to include static models of organizations [10] and products [11]. The new millennium brought an explosion of DSM research and applications across multiple industries and contexts. Browning's [12] 2001 review of the DSM literature (also in these TRANSACTIONS) cited about 100 DSM papers; there have been over 1000 since. These developments are of great interest to researchers[1] and practitioners; therefore, it is valuable to provide an organized account of the evolving landscape to consolidate progress and provide a foundation for further advancement. Primarily targeting practitioners, Eppinger and Browning's recent book [13] provided an introduction to DSM methods along with 44 industrial application examples. Primarily targeting researchers, this paper surveys recent DSM extensions and innovations in the scholarly literature and illuminates areas with a plethora of publications as well as areas offering excellent research opportunities.

A DSM (see Fig. 1) is a square matrix where the diagonal cells typically represent the system elements (such as components in a product, people in an organization, or activities in a process) and the off-diagonal cells represent relationships (such as dependencies, interfaces, interactions, etc.) among the elements. DSMs containing a single kind of off-diagonal mark are

[1] [5] and [12] are the second- and third-most cited papers, respectively, out of over 1,900 papers in the 60+ year history of *IEEE-TEM*, according to the Web of Science, September 14, 2015).

called binary DSMs, and DSMs with off-diagonal cells containing a number are called numerical DSMs. Other types of DSMs may contain a variety of symbols, markings, and color coding, as the format lends itself to customizations. The literature contains two conventions for matrix orientation. In the first, an element's inputs appear in its matrix row and its outputs appear in its column. This is called the "inputs in rows" convention [13]. The second convention, with "inputs in columns" (IC) and outputs in rows, is merely the transpose of the matrix and conveys the same information. (Both conventions persist because each has advantages in particular contexts, and because of the diverse roots of the matrix-based models now called DSMs.) The regions above and below the diagonal in the matrix, thus, distinguish the directionality of any relationships, making the basic DSM equivalent to a directed graph. However, in some circumstances and to many users, the DSM representation has advantages over a graph (or node-link diagram or flowchart): the DSM is relatively more compact, scalable, and readable with increasing size while easily highlighting important architectural characteristics such as modules and cycles (e.g., process iterations or rework loops) [12], [14]. The goal of the DSM is to expose the structure of a system's architecture or design. Aside from this minimal introduction, this paper will presume that its readers already possess a basic familiarity with DSM. (See [13] for a thorough introduction.)

For this survey, we assembled and studied a vast collection of papers[2] from journals, books, and conference proceedings. Because Browning's review [12] covered developments through 2000 (although appearing in 2001), we focused mainly on (post-2000) works. We began in late 2011 by conducting a citation search on a set of prominent DSM papers [4], [5], [12], [15], [16], which identified over 3000 citations (many redundant). We supplemented these results with a general search of the academic literature (including journals in engineering management, operations management, project management, engineering design, management science, organization science, and systems engineering) from 1998 to 2012 for the keywords "design structure matrix" and "dependency structure matrix." This produced more than 100 additional references. Next, we explored the reference lists of these works in search of further items. Finally, we added many recent papers from 2012 to 2015. Altogether, we were able to identify over 1300 papers,[3] of which we could acquire and read over 1000 complete items. Next, we read each paper to determine if it actually applied DSM (versus merely mentioning it) and, if so, attempted to classify it by Browning's [12] taxonomy—i.e., whether the paper used a static or a temporal DSM to model a product architecture, an organization architecture, a process architecture, or more than one of these. We encountered some papers that did not fit this taxonomy, which prompted us to expand it to include project *tools* and *goal* architectures.

Space constraints in this paper forced a downselect from the full list of papers in the survey.[4] We focused primarily on the scholarly papers in archival peer-reviewed journals, although we do include some selected conference papers, book chapters, and theses. One prominent area that receives admittedly limited coverage is the set of papers from the annual DSM conferences (www.dsm-conference.org). Although these (and many other conference) papers are obviously relevant, we mostly omit them because of space limitations and because many of the best of them have matured into journal papers (which are included).[5] We also omit some papers where authors superseded their earlier works with more advanced or similar ones. Space constraints also do not permit a detailed exploration and comparison of each of the vast number of papers in the DSM literature. Rather, this paper's goal is to survey the landscape, summarize the main thrusts of research to date, and illuminate propitious opportunities for further research.

This paper begins by surveying advances in and opportunities for traditional DSM applications—models of products, organizations, and processes. Innovations and extensions in each of these three areas are presented in terms of building, displaying, analyzing, and using the models. Many applications are also distinguished by industry. Successive sections address newer DSM application areas, DMMs, and MDMs, respectively—again accompanying the survey with several opportunities for further research.

II. Advances in and Opportunities for Traditional DSM Applications

Browning's [12] review laid out the three types of DSM applications—models of products, organizations, and processes. (Browning's fourth type, a parameter-based DSM, is essentially a high-fidelity process DSM.) These three domains have received the bulk of scholarly and industrial attention to DSM. This section surveys key advances and discusses promising opportunities for further progress in each of these three areas. Although Steward originally developed the DSM for processes, this section will begin with static DSMs (product and organization) before proceeding to temporal (process) DSMs. Each of these three applications will be presented with a brief history followed by a discussion of the literature organized around the building, display, and analysis of the DSM, further uses, and cited examples of application instances in particular industries. Note that many of the developments pertaining to building and displaying each of these DSM types can often be leveraged across all types of applications.

A. *Product Architecture DSMs*

Square-matrix models of product structures, which we call product architecture DSM models (or product DSMs for short), grew from several sources. The use of square matrices to model

[2]For convenience, we refer to all articles, books, chapters, reports, and theses as "papers."

[3]These papers included over 100 non-English papers, of which about two-thirds are in Chinese and the rest in German, French, Korean, Spanish, Japanese, Portuguese, Dutch, and Italian—in order of decreasing frequency.

[4]We are adding our full list of DSM references to the database at www.dsmweb.org. Anyone with awareness of additional references can submit them to this list.

[5]Surveying the papers from the 17 annual DSM conferences presents an excellent opportunity for future research.

TABLE Ia
PRODUCT ARCHITECTURE DSM INNOVATIONS AND EXTENSIONS—WITH SELECTED REFERENCES

Building Product DSMs	Selected References
Increasing model consistency and inter-rater reliability	[21]–[25], [83]
Distinguishing types and strengths of interfaces/relationships	[11], [22], [41], [51], [57], [303]–[305]
Constructing software architecture DSMs automatically from source code	[26], [27], [306], [307]
Constructing a product DSM automatically from other models	[28]–[31], [113], [308], [309]
Building function-to-function, concept-to-concept, and other types of product DSMs	[20], [32]–[37], [39], [40], [257], [310], [311]
Displaying Product DSMs	**Selected References**
Showing nested module/subsystem structures with hierarchical DSMs	[13], [21], [26], [109], [312]–[314]
Showing varied types and strengths of interfaces/relationships	[11], [41], [250], [315]
Showing change probability and impact as mini-graphs in the DSM	[42], [52], [53]
Using DSM appendages to show external relationships	[12], [22], [43], [309], [316]
Showing multiple product variants with a three-dimensional DSM	[44]
Analyzing Product DSMs	**Selected References**
Determining product modules	[58], [317]
Determining modules via clustering analysis	[46], [47], [50], [56], [311], [318]–[327]
Clustering via evolutionary algorithms	[41], [45], [328]–[337]
Clustering with the criterion of intellectual property protection when outsourcing	[48], [49]
Clustering with the criterion of component volatility and option value	[43], [338]
Sequencing to determine architectural levels	[51], [339]
Analyzing change propagation	[42], [52]–[54], [277], [289], [340]–[344]
Calculating modularity metrics	[21], [29], [55], [62], [315], [345]–[347]
Calculating other metrics (e.g., row and column sums to ascertain interface intensity and priority, fan-in and fan-out, degree of connectivity, visibility, etc.)	[27], [221], [282], [312], [348]
Expanding or dithering the matrix to differing levels of detail	[349]
Calculating the difference between two DSMs as a "delta DSM" (DDSM)	[35], [350], [351]

system architectures can be traced back to the works of Simon [17] and Alexander [18] in the early 1960s. Steward created the process DSM model (see Section II-C) in the 1960s, yet it was not until the early 1990s that Pimmler and Eppinger at MIT applied the DSM to model the product architecture [11]. Meanwhile, practicing systems engineers have used the "N-square" chart to model and manage the component interfaces since the 1970s (at the latest), when it was formally codified by Lano [19]. Since the 1990s, product DSMs and N-square charts have continued to converge somewhat in the systems engineering literature.

For the purposes of this survey, a product is an engineered system, such as an automobile, an aircraft, an electronic system, a software application, a machine, a mechatronic unit, a building or built environment, a piece of capital equipment, etc. A product system has a design structure, or architecture, "the arrangement of components interacting to perform specified functions. The architecture of a product is embodied in its components, their relationships to each other and to the product's environment, and the principles guiding its design and evolution" [13]. A product consists of components related in various ways, such as spatially or based on a flow of material, energy, or information. Product architecture models could include at least three mappings [13]: 1) a hierarchical decomposition of the product into modules and components, often represented with a product breakdown structure (PBS); 2) an assignment of the product's functions to its components and modules, often represented with a rectangular mapping matrix; and 3) the relationships among components and modules, often captured with a product DSM. DSMs have also been used to model function-to-function relationships in the product domain (e.g., [20]). See [13] for further discussion of the motivations for and benefits of the product DSM models. Because of their usefulness in product design and development, product DSMs have gained particular traction in the engineering design and systems engineering communities, although they have also begun to receive attention in operations management and software development contexts. Recent product DSM models have brought many innovative applications (see Table Ia and b). The remainder of this subsection surveys several of these while noting opportunities for further research and development.

1) Building Product DSMs: Product DSMs are challenging to build because of the large amount of included knowledge, and because of varied interpretations of a product's decomposition and structural relationships. Different modelers build different models by choosing different levels of decomposition (abstraction), component definitions at each level, and relationship types and definitions among the components [21]–[25]. Because different models yield different metrics (e.g., amounts of modularity) and analysis results (e.g., module definitions), increasing the "inter-rater reliability" of DSMs is an important area for further research. Accordingly, Tilstra *et al.* [22] proposed a standardized approach for building product DSMs to increase consistency across modelers. Needs for consistency and reduced effort in model building have driven the development of approaches for automatic extraction of DSMs from existing databases. Sangal *et al.* [26] and MacCormack *et al.* [27] demonstrated the efficacy of this approach for software products by building large, rich, consistent DSMs from source code repositories. Product DSMs have also been extracted from unified modeling language (UML) models [28]–[30] and a function-behavior-state model [31]. With further development, it should become possible to extract DSMs automatically from CAD models or other standardized frameworks, such as building information models (BIMs). On a related point, most product DSMs built to date have modeled physical components and their relationships (e.g., spatial, material flow, energy flow, and data flow). However, functions are also an important aspect of the product architecture, and function-to-function DSMs have been used by several researchers (e.g., [20], [32]–[37]). (Function-to-component mappings will be discussed in Section IV.) Functional dependencies could also be added to the component-based product DSM models [38]. Static DSMs have also been used to show relationships among design concepts (e.g., [39]) and design constraints [40]. While many possibilities exist to develop additional flavors and varieties of product DSMs, opportunities remain to develop standardized approaches for building them.

2) Displaying Product DSMs: Recent work has brought several innovations in the display of DSMs in general and product DSMs in particular. Colors and shading provide powerful ways of indicating the hierarchy of nested modules, and display tools can expand and contract areas of a DSM to drill down to deeper levels or roll up to higher levels (e.g., [26]). (These capabilities are important to other types of DSM models as well; e.g., see Section II-C2.) Many product DSMs capture more than one type of relationship among components, and showing more than one of these at once in a single matrix presents a challenge of crowding. One can portray relationship type in subcells (e.g., [11], [41])—although this quickly crowds the matrix—or in separate matrix layers or planes (e.g., [22]). To reveal visual insights, symbols (e.g., [10]) work better than numbers alone, especially for large DSMs. Clarkson *et al.* [42] provided an innovative way to combine the probability and impact of a change propagating across an interface by placing a minigraph in each off-diagonal cell, where the width of the graph represents probability, the height of the graph represents the impact, and the shaded area of the graph represents the risk (the product of probability and impact). Relationships with external entities can be modeled by adding a row and column to the DSM [22], [43] or by using separate regions above and to the right of an IC-convention DSM [12]. Alizon *et al.* [44] overlaid DSM layers, each representing a product variant, to compose a three-dimensional DSM depicting a product family. Further opportunities abound to develop DSM display approaches that make helpful use of hierarchy, layers, numbers, colors, and symbols and provide the capabilities to expand and contract regions and link to additional sources of information about the components and their relationships.

3) Analyzing Product DSMs: Although some additional analyses have been developed for product DSMs, most analyses to date have focused on clustering components to determine modular architectures. Advances in clustering include the use of sophisticated genetic algorithms (e.g., [41], [45]), analysis of the eigenstructure of the matrix [46], approaches from graph theory [47], and the use of criteria besides simply the number of interfaces inside or outside a cluster, such as the likelihood of component change [43], the probability of unintended intellectual property transfer when outsourcing [48], [49], or module commonality across a product family [50]. Although improved approaches to clustering and other DSM optimization problems are useful, the primary challenges here lie in the determination of appropriate objective functions for multicriteria optimization and the interpretation of results. Besides clustering, since an earlier DSM review [12] suggested the possibility of applying sequencing analysis (usually applied to temporal DSMs) to static DSMs, this has been done for both software (see Section III) and hardware [51]—in part to separate the product architecture into hierarchical levels (with higher levels depending on lower levels but not vice versa) to facilitate product design and development. Aside from clustering and sequencing, product DSMs have also been analyzed in terms of the probability and impact of a component change propagating across an interface, which has enabled the determination of the riskiest paths of change propagation and the designation of components as change multipliers or absorbers [42], [52]–[54]. This analysis can help designers to adjust components and interfaces to manage product modularity and evolution. Still other analyses have used DSMs as the basis for calculating various metrics, especially pertaining to modularity (e.g., [21], [46], [55]). An acute challenge here is to devise a scale-free metric, one that gives the same result for a given product regardless of the level of decomposition (matrix size).

4) Otherwise Benefiting From Product DSMs: Researchers have developed a number of innovative ways to use product DSM models. Several of these applications are summarized in Table Ib. Sharman and Yassine [56] used the DSM to identify architecture characteristics, patterns, or signatures such as buses, asymmetry, imperfection, pinning, and holding away. Fixson [57] explained the importance of interface reversibility and standardization. Baldwin and Clark (e.g., [58]) emphasized the strategic and economic implications of product architectures and designs. Here, the product DSM literature has many connections with the broader literature on modularity. Facilitated by a product DSM, modularity has informed design evolution (e.g., [55], [59]–[61]), outsourcing decisions [49], [62], and market or portfolio segmentation (e.g., [63]). Moreover, the product DSM has supported design for variety while maximizing component commonality across product families or platforms (e.g., [64]–[67]) and design for adaptability, often via modularity and its connection with *real options* (e.g., [43], [68], [69]). The insights from these applications are quite sophisticated, but their wider use in practice will require new and improved software tools to support DSM model building, analysis, and interpretation. The use of multiple DSMs for product variants could benefit from the development of a "logic DSM" that represents relationships such as "if using component A then also use component B but not component C." Baldwin and Clark [58] also elucidated the importance to good architecting of design rules—what designers working in decoupled modules follow to assure later ease of integration. Some have used DSMs to help to determine the need for and location of additional design rules, as well as to locate and flag rule violations (e.g., [26], [28], [70], [71]). However, while Baldwin and Clark introduced design rules using a hardware example, most subsequent work has applied the concept to software. Further research could demonstrate the power of,

TABLE Ib
PRODUCT ARCHITECTURE DSM INNOVATIONS, EXTENSIONS, AND APPLICATION AREAS—WITH SELECTED REFERENCES

Otherwise Benefiting from Product DSMs	Selected References
Determining architecture patterns or signatures and their implications	[56], [57]
Assessing the strategic and economic implications of product architecture	[57], [58], [60], [339], [352]–[356]
Using modularity to inform design evolution	[55], [59]–[61], [357]–[359]
Using modularity to inform outsourcing and partnering decisions	[49], [62], [360]
Segmenting portfolios	[63]
Designing for variety, component commonality/reuse, and product platforms/families	[38], [39], [44], [64]–[68], [305], [361]–[368]
Designing for adaptability/flexibility/changeability (often via modularity, real options)	[22], [43], [68], [69], [304], [338], [369]–[375]
Determination and use of design rules in product design	[26], [28], [58], [70], [71], [376], [377]
Using design rules and options for mass customization	[378]–[380]
Standardizing and managing interfaces	[57], [70], [376], [381]
Designing for manufacturing and assembly (DFMA)	[382]
Designing for sustainability and the environment	[316]
Synthesizing with other design methods and tools such as QFD, Axiomatic Design, and the Theory of Inventive Problem Solving (TRIZ)	[67], [257], [356], [361], [383]–[387]
Decomposing and optimizing design problems	[72], [73]
Supporting MDO	[74]–[76], [388]
Exploring the conceptual design space	[308], [383]
Managing product knowledge	[78]
Analyzing product usability	[389]
Supporting reverse engineering	[22], [40], [390]
Integrating systems and infusing new technologies	[350], [387], [391]
Analyzing system integration and testing	[392]
Allocating resources to product modules	[393]
Industry Instances	**Selected References**
Aerospace	[13], [41], [42], [52], [53], [75], [76], [98], [308], [315], [340], [342]–[344], [375], [383], [394], [395]
Automotive	[11], [31], [35], [38], [67], [260], [311], [318], [341], [351], [362], [378]–[380]
Computer (hardware)	[51], [58], [339], [395]
Construction	[74], [304], [312]
Electronics	[21], [66], [350], [357], [364]–[367], [375], [395], [396]
Energy	[68], [250], [392], [397]
Information technology	[398]
Manufacturing systems	[62], [335], [345], [373], [375], [399]
Mechanical products/equipment	[36], [37], [50], [72], [305], [316], [321], [325], [335], [368], [400]
Sensor systems (large-scale)	[289]
Service system design	[324]
Ship design	[362], [401], [402]
Software	[14], [27], [28], [30], [59], [70], [71], [102], [306], [313], [376], [403], [404]

and explore approaches to formalizing, design rules for hardware products. Additional studies of architecture evolution from a longitudinal perspective would also be helpful. These could employ a set of static DSM models collected periodically or at set points of architecture change. The ease with which certain architecture patterns (e.g., modularity) correspond with hypothesized developments (e.g., the exercising of real options) could thereby be explored empirically.

Table Ib also notes several other recent applications of product DSMs. Space will not permit detailing these, yet it is worth mentioning the expanding use of DSMs in design optimization (e.g., [72], [73]), particularly multidisciplinary design optimization (MDO) [74]–[76]. Although MDO applications at NASA marked some of the earliest applications of process DSMs (e.g., [9], [77]), the more recent design optimization models noted here have used product DSMs. MDO work has necessarily dealt with the approach to and level of decomposition of a product design problem, an area where further work could beneficially align with the work on repeatable approaches to building product DSMs (see Section II-A1). Akin to the DSM work on change propagation, the MDO-related work has explored the use of DSMs as sensitivity matrices at the parameter level, thereby supporting design trade studies.

Furthermore, product DSMs show potential as a part of an overall solution to knowledge management challenges (e.g., [78]). By providing a structure for organizing product knowledge in terms of both the PBS and the component relationships, the product DSM can provide a concise interactive overview of a complex product with links to further information (design specifications, design rules and guidelines, lessons learned, etc.) about particular components and interfaces. Further work in this area is needed, and it should draw from the related research on building and representing product DSMs (see Sections II-A1 and II-A2), as well as research discussed later about comparable opportunities with process DSMs (see Sections II-C1 and II-C2). Finally, Table Ib notes some of the growing breadth and depth of industry instances; it includes only ones reported in the literature—surely a mere fraction of actual applications. (Note that further models of software architectures are addressed later in Section III.)

TABLE II
ORGANIZATION ARCHITECTURE DSM INNOVATIONS, EXTENSIONS, AND APPLICATION AREAS—WITH SELECTED REFERENCES

Building Organization DSMs	Selected References
Documenting relationships among organizational units	[80]
Using a survey instrument to gather data on organizational unit relationships	[81]–[83]
Deriving an org DSM from a process DSM	[84], [85]
Extracting relationships automatically via communication data mining	[86]
Capturing dependencies among skill sets	[87]
Modeling organizational work and coordination time	[88]
Displaying Organization DSMs	**Selected References**
Use of symbols instead of numbers	[13]
Showing hierarchy and membership in organizational structures	[13]
Analyzing Organization DSMs	**Selected References**
Clustering to determine organizational structures	[89]–[91], [326]
Identifying communication gaps and overlaps	[82]
Longitudinal analysis of multiple static DSM "snapshots"	[13], [82]
Optimizing work allocation across global product development organizations	[88]
Sequencing of organizational units to identify cooperation groups	[93]
Applying social network analysis techniques and metrics	[94], [95], [405]–[407]
Decomposing a social network into an optimal number of structurally equivalent classes	[408]
Otherwise Benefiting from Organization DSMs	**Selected References**
Comparing org and product architectures	[30], [97]–[104], [409]
Determining optimal team assignments	[90]
Designing organizations for integration (DFI), applying appropriate IMs	[13], [82], [410], [411]
Reorganizing projects at each phase due to changing needs for communication	[30], [82], [104], [412]
Managing interorganizational and supplier integration	[412], [413]
Determining clusters of related skill sets	[87]
Identifying misfits or misalignments among organizational units	[105]
Determining the organizational impacts of product change propagation	[414]
Identifying indirect relationships among stakeholders	[81]
Examining implications of organizational interactions on organization design	[411], [415]–[417]
Industry Instances	**Selected References**
Aerospace	[13], [82], [87], [94], [98], [104], [105], [405], [409], [412], [418]
Automotive	[91], [278], [406], [414]
Electronics	[88]
Energy	[13], [81]
Innovation systems	[13]
Software	[30], [102]
Transportation system organizations	[89]

B. Organization Architecture DSMs

For the purposes of this survey, an organization is a network of people (or groups thereof) with a common purpose. As a kind of system, an organization has an architecture—its structure, "embodied in its people, their relationships to each other and to the organization's environment, and the principles guiding its design and evolution" [13]. Generally, an organization consists of "organizational units" such as teams, departments, agents, or individuals that connect to each other in various ways. Organization architecture models could include at least three mappings [13]: 1) a hierarchical decomposition of the organization into units; 2) work assignments and top–down reporting relationships (lines of authority) among the units; and 3) lateral relationships among the units. The first two of these are often represented with an organization breakdown structure or "org chart," whereas the third has been the main focus of organization architecture DSM models ("org DSM" for short).

Although Lano had previously used the "N-square" chart to model organizational interfaces [19], and others had used square matrices to model organizational communication flows (e.g., [79]), McCord and Eppinger [10] developed the first explicit org DSM model. Meanwhile, others such as Coates *et al.* [80] used matrix models with names like "agent matrix." Browning's [12] review distinguished product and org DSMs as separate applications of static DSMs. Eppinger and Browning [13] further described the motivations for and benefits of org DSM models. Recently, org DSMs have enabled many innovative applications (see Table II), gaining attention especially in management/organizational science contexts. The remainder of this subsection surveys several of these areas while noting opportunities for further research and development.

1) Building Organization DSMs: In one way, building an org DSM can be less difficult than building a product DSM because the lowest granular unit for decomposition (i.e., an individual person) is more commonly understood, and there is usually less ambiguity about the initial definitions of higher-level units such as departments or teams (because these are usually taken as given from readily available sources). Thus, while no empirical results yet exist, "inter-modeler reliability" (cf., "inter-rater reliability") might be higher for org DSMs than for product DSMs. Most org DSM models have focused on information flow relationships and have been built through surveys or interviews of the organizational units or their representatives (e.g., [81]). However, such an approach can reveal a large discrepancy between the provider and receiver perspectives of the respondents [82], [83]. In such cases, Browning [82] suggested simply taking the maximum of the two responses, since communication networks in project organizations seem to be much richer (and their DSM representations much denser) than initially supposed by either the provider or receiver perspectives (although empirical confirmation of this conjecture is needed). Some researchers [84], [85] have used a process DSM to derive an org DSM. Dabbish *et al.* [86] extracted relationships by mining communication data but also found that using different sources and types of relationship data could yield very different DSMs. Further research should examine the relative efficacies and accuracies of alternative methods for building org DSM models. Also, although the focus of most org DSMs has been the frequency of information flow among organizational units, others have used it to model the dependencies among organizational skill sets [87] and the amount of work and coordination time spent by the units [88]. Future research could elaborate on the varieties and possibilities of org DSMs to model other types of relationships among organizational units.

2) Displaying Organization DSMs: In comparison to product DSMs, relatively little has been done specifically regarding the display of important organizational patterns in a DSM. Eppinger and Browning [13] exhibited some recent innovations in this area from various sources, including the creative use of symbols and colors to indicate the strength of relationships and the use of boxes, colors, and multiple matrix entries to indicate the membership of units in hierarchical structures. Fortunately, because both are static DSMs, many of the visualization techniques pertinent to product DSMs (see Section II-A2) can be leveraged for org DSMs (and vice versa).

3) Analyzing Organization DSMs: As with product DSMs, the bulk of org DSM analysis has focused on clustering, primarily of organizational units, as a means of assigning them to higher-level groupings (e.g., [89]–[91]). The clustering methods used are similar to those discussed previously for product DSMs (see Section II-A3), including the equivalent use of a "bus threshold" to isolate units with high interactivity with the overall organization. (Such units may then be designated as "system engineering," "integration," or "management" units and removed from further consideration in the clustering analysis [13].) However, opportunities remain to develop clustering algorithms tailored to organizational applications and based on empirical justifications, where the objective function contains factors and values pertinent to the particular situation. Although analysis tools such as Ucinet [92] provide the capability to generate a specified number of clusters, it would be helpful to incorporate greater clustering functionality into DSM tools. Some simpler analyses of org DSMs have used row and column sums (essentially in-degree and out-degree) to gauge a unit's relative communication burdens and suggested examining the DSM to identify communication gaps and overlaps among units [82]. Furthermore, because an organization is a dynamic system, and a static DSM only captures a snapshot of a system at a point in time, multiple DSMs can be stacked for longitudinal studies of organizational change. Browning [82] used two DSMs to show the situation in a product development organization before and after an 18 month interval, during which the communication frequencies among particular units changed significantly. Tripathy and Eppinger [88] developed a quantitative model of work and coordination times for each organizational unit and used these to optimize the allocation of work across units. Rondeau *et al.* [93] essentially sequenced an org DSM to identify cooperation groups and explore their implications. Finally, several scholars (e.g., [94], [95]) have applied social network analysis techniques to org DSMs: further synthesis and analyses of these models promises to be a very fruitful area of DSM research.

4) Otherwise Benefiting From Organization DSMs: Org DSMs have also propelled research in other areas. One of these areas concerns the relationship between product and organization architectures, particularly with respect to Conway's [96] assertion that an organization will inevitably design products whose structure copies that of the organization's communications. In addressing this "mirroring hypothesis," Colfer and Baldwin [97] presented "actionable transparency," which has the effect in the org DSM of routing technical communication through a "bus element" (such as a shared database) that provides a surrogate for direct communication. Hence, it is an example of how an integrative mechanism (IM) could be represented as an alteration in an org DSM. Several scholars (e.g., [30], [98]–[104]) have explored the alignment (or lack thereof) between the product and organization architectures in engineering projects and proposed connections to various aspects of project performance. These studies provide excellent examples of where the DSM has supported the top-notch research in the organization science and engineering management domains. Future studies could consider the alignment of the organization architecture with other project architectures such as the process, tools, and goals. Table II provides several other examples of where an org DSM has supported various strands of organizational research. Each of these areas could be extended, and researchers who work with graph-based network models could unlock potential benefits and insights through the use of an org DSM representation. Again, a particular area for further research concerns the longitudinal study of organizations (e.g., [30], [82], [104])—perhaps through the use of a set of org DSMs, where each provides a snapshot of the organization architecture at a different point in time. Such studies could add to our knowledge of organizational dynamics, adaptation, and evolution.

Finally, Table II notes several industrial instances of org DSMs at entities such as NASA [105], General Motors, McDonnell Douglas, Pratt & Whitney, Timken, and BP [13]. Aerospace instances figure most prominently in the literature.

C. Process Architecture DSMs

The DSM moniker was first coined by Steward for his square-matrix-based models of processes [3]–[5], which emerged from his earlier use of such matrices for solving the systems of equations [1], [2]. Since then, process architecture DSM models ("process DSMs" for short) have received the most attention of all DSM application areas from scholars and practitioners. Prominent early efforts include work at NASA [9], [77], MIT [8], [16], [106], and The Boeing Company [107].

A process is "a system of activities and their interactions comprising a project or business function," and a process architecture is a process's structure, as determined by its constituent activities and their interactions, and the principles guiding its design and evolution [13]. Process architecture models include at least three mappings: 1) the hierarchical decomposition of the process into activities; 2) the input–output relationships among the activities; and 3) other types of activity relationships. The process DSM models the second of these, although it can also show the first. The third usually requires object-oriented modeling techniques. Hence, a rich process model may fully exist only in a database, of which a process DSM could provide a partial view; flowcharts and Gantt charts are examples of additional partial views [108]. A DSM view is especially advantageous when seeking to highlight cycles (iterations or rework loops), which are both prominent and problematic in project processes. See [13] for the further discussion of motivations for and benefits of process DSM models. Process DSMs have gained traction mainly in engineering design and construction management. Recent models have brought many innovative applications (see Table IIIa and b). The remainder of this subsection will discuss several of these along with opportunities for further research and development.

1) Building Process DSMs: Process modelers have taken a variety of approaches to building DSMs, including leveraging existing documentation and models in other formats (e.g., flowcharts), interviews, and surveys. Interviews and surveys can be more or less effective depending on the questions asked and the understanding and expertise of the respondents. Although existing models and documents offer convenience, they tend to produce relatively sparse DSMs that account for only a minimal number of activity dependencies [109]. Because a DSM does not increase in size with the number of dependencies (only with the number of elements), it provides an advantageous platform for capturing and displaying richer models of the extensive information flows among activities. A powerful way to build such models is to build two DSMs, one row-by-row and the other column-by-column—by separately collecting the input and output perspectives of an expert on each activity—and then overlay these [83], [110]. The data collection may not even use a DSM but rather a set of supplier-input-process-output-customer (SIPOC) diagrams, the content of which is then transferred to a DSM format. This approach tends to uncover many differences in understandings among the activity experts, and yield a much richer model of the information and work product flow (often 3–5 inputs and outputs per activity instead of the 1–2 typical of many flowcharts). Researchers have explored several ways to increase the process DSM model-building accuracy and efficiency, such as determining activity dependencies from product models [111]–[113], document flow data [114], [115], e-mails [116], or observed rework loops [117]. Web-based tools have provided another means of distributing and automating the process of data collection [118], [119]. Others have used quality function deployment (QFD) as a basis for modeling activities and dependencies [111], [112], [120]. To build a large DSM, still others have taken the approach of integrating several smaller DSMs [109], [121].

Whereas a particular challenge in modeling product design and other novel project processes is activity and dependence ambiguity, Austin *et al.* [122] nevertheless found that even 79%–90% of conceptual design activities could be specified and modeled. Others [123]–[125] provided ways to account for uncertainty or ambiguity in activity dependencies—e.g., with "fuzzy" dependence specifications. Clarkson and Hamilton [126] and Lévárdy and Browning [127] proposed the use of alternative *activity modes* to capture various ways an activity could be undertaken (e.g., a slower and cheaper mode versus a faster but more expensive mode, or an initial mode versus a rework mode). Yassine [128] detailed the elicitation of rework probabilities for DSM models that seek to include them. Indeed, many of the more sophisticated DSM models require a variety of additional inputs that must be acquired from experts while taking similar caution. Overall, building process DSMs often requires significant effort, although it is important to recognize that this effort is really spent on building a good process model: once that exists, rendering part of it as a DSM is essentially instantaneous.

2) Displaying Process DSMs: A DSM cannot display a rich process model in its entirety. Some attributes of activities (e.g., duration) or dependencies (e.g., requirements) are not typically shown in a DSM, and, even if they were, this would preclude showing other attributes such as activity costs or rework probabilities. The conciseness of the matrix format limits the number and kinds of attributes that may be usefully shown at once. Hence, Browning [108], [129] proposed a process architecture framework that combines DSM with many other views of a process model, thereby circumventing some of the classic tension between model simplicity and completeness. Otherwise, regarding the display of process DSMs, many of the innovations discussed previously with respect to displaying product and org DSMs (see Sections II-A2 and II-B2) can also be applied. One situation that tends to appear more often in process models is the presence of conditional or contingent relationships among activities. A few papers [12], [126], [127] have developed special symbols (e.g., diamonds like the ones used in flowcharts, "♦") to signify alternative flow paths. However, further research, applications, and display enhancements of DSMs with conditional flows are needed. Users of process DSM models seeking to isolate various process threads or tailor a process would benefit from tools with the capability to highlight such threads. Display tools could also better support model building by highlighting missing elements, such as disconnected flows of work products. Separately, much like project scheduling models have activity-on-arc and activity-on-node representations, it would be interesting to explore the possibilities of DSMs with deliverable, work product, or information objects on the diagonal and activities in the off-diagonal cells [130].

3) Analyzing Process DSMs: A great amount of research has focused on the analysis of process DSMs. Most analyses seek

TABLE IIIA
PROCESS ARCHITECTURE DSM INNOVATIONS AND EXTENSIONS—WITH SELECTED REFERENCES

Building Process DSMs	Selected References
Using SIPOC diagrams and deliverable negotiations to formalize interfaces	[109], [110]
Facilitating data collection in workshops	[25], [83], [419]
Constructing a process DSM automatically from other models	[108], [113], [129], [210]
Deducing a process DSM via e-mail analysis	[116]
Mapping document flow	[114], [115]
Counting defects and rework loops	[117]
Distributing and automating data collection via web-based tools	[118], [119], [420]
Using QFD to determine activities or dependencies	[111], [112], [120]
Integrating smaller DSMs	[109], [121], [421], [422]
Modeling conceptual design activities	[122], [423]
Accounting for uncertainty or ambiguity in activity dependencies	[123]–[125], [420], [424]–[426]
Accounting for multiple activity modes	[126], [127]
Eliciting rework probabilities	[128]
Displaying Process DSMs	**Selected References**
Providing multiple views of a process model, including DSM	[108], [129], [427], [428]
Representing contingent relationships	[12], [126], [127]
Varying colors, symbols, shading, numbers, etc.	[12], [13], [220], [429]
Using DSM appendages to show external relationships	[12], [13], [109], [430]
Working with very large and/or hierarchical matrices	[14], [109], [431]
Focusing the DSM on deliverable or information objects	[130]
Analyzing Process DSMs	**Selected References**
Sequencing activities in processes (basic)	[5], [16], [131], [271], [432]–[440]
Decomposing coupled blocks	[133]–[144], [433], [441]–[452]
Overlapping activities	[145]–[147], [150], [453]–[455]
Scheduling project workflows	[80], [124], [151]–[157], [195]–[197], [203], [322], [454], [456]–[467]
Estimating iterative process duration and/or cost	[15], [153], [158]–[160], [162], [188], [194], [205], [430], [453], [468]–[480]
Estimating effects of iterative process on process duration and cost, as well as on the technical performance of a developing product	[127], [161], [481]–[483]
Estimating iterative process variability, robustness, and/or risk	[15], [128], [147], [479], [484]
Optimizing process duration or cost (often with an evolutionary algorithm)	[133], [147], [149], [163]–[167], [190], [191], [433], [485]–[497]
Optimizing multiple objectives (e.g., process duration and cost)	[168], [169]
Analyzing process convergence	[159], [170]–[173], [429], [471], [474], [498]–[501]
Applying network analysis techniques (e.g., social networks)	[174], [175], [424], [502]
Clustering activities or design parameters/decisions	[12], [137], [138], [142], [150], [176]–[182], [460], [468], [503], [504]
Sequencing and/or prioritizing design parameters/decisions	[112], [155], [183]–[186], [505], [506]
Analyzing processes while accounting for resource allocations	[162], [187]–[191], [271], [477], [479], [495], [507]–[509]
Exploring effects of project work policy and activity crashing and overlapping	[148]

to identify an advantageous sequence of activities by reordering the matrix rows and columns. Many begin with some form of matrix block triangularization—i.e., the minimization of feedbacks and the identification of coupled blocks of cyclical activities. Although the literature contains several algorithms (e.g., [131]), Tarjan's [132] depth-first search provides the most efficient way to identify coupled components [133]. Once coupled blocks have been found, further analyses have been proposed to sequence the activities within each block, including tearing (e.g., [5], [134]), eigenvalue analysis (e.g., [135], [136]), analytic hierarchy process (e.g., [137]–[141]), clustering (e.g., [138], [142]), implied organizational structures (e.g., [137], [143]), genetic algorithms (e.g., [133]), iteration front-loading [144], and others. Most of these approaches entail collecting additional information about the dependencies among the coupled activities and utilizing these data in a more sophisticated optimization. One of the basic tradeoffs in such cases is that between increased overlapping, parallelism, and concurrency versus the concomitant increase in iteration and rework—i.e., which activities should be executed sequentially or in parallel. Here, the DSM touches the broader literature on activity overlapping, sometimes explicitly (e.g., [145]–[150]). Ultimately, activity sequencing boils down to decisions about when to start and stop each activity—i.e., project scheduling (with some expected number of activity iterations)—although many of the aforementioned analyses of coupled blocks do not go this far.

Several other process DSM analyses derive actual project schedules or "run-time models" (e.g., [80], [151]–[157])—sometimes by side-stepping some of the thornier issues of coupled blocks with simplifying assumptions. These works mainly use the DSM as an intermediate step on the way to producing a workflow or Gantt chart view of a project plan. Several of these developments have focused on the building construction industry, where detailed schedules are the expected deliverable from any planning exercise.

The effects of iteration and rework cycles on project duration and cost are difficult to forecast. Smith and Eppinger developed analytical models to estimate project duration assuming sequential activities [158], parallel activities [159], or a combination [160]. Processing more general cases requires simulation. The first DSM-based discrete-event Monte Carlo simulation model [15], [161] estimated project duration and cost, as well as the

TABLE IIIb
PROCESS ARCHITECTURE DSM INNOVATIONS, EXTENSIONS, AND APPLICATION AREAS—WITH SELECTED REFERENCES

Otherwise Benefiting from Process DSMs	Selected References
Structuring project organizations and/or supplier networks	[142], [180], [199]–[201], [270], [510]
Managing product configurations/variants for sales and production	[511]
Predicting the effects of design/requirements/engineering changes on a project	[202]–[205], [479]
Evaluating process improvements	[206]–[208]
Quantifying project uncertainty	[512]
Investigating the implications of process characteristics on performance	[513]
Prioritizing activities	[209], [483]
Identifying process flow disconnects	[15], [210]
Modeling causes and flows of events	[514]
Exploring the implications of alternative sequences of conceptual design parameters	[186]
Situating verification, validation, and testing activities in a design process	[193], [211]
Monitoring project/design progress	[212], [506]
Analyzing resource dependencies across projects in a portfolio	[187]
Managing resources and/or scheduling in a manufacturing system	[213], [214], [515]–[517]
Managing dimensional tolerances and process capability in production	[505]
Modeling the product development process as a complex adaptive system (CAS)	[127], [518]
Facilitating MDO	[75], [77], [215]–[217], [388], [498], [499], [519], [520]
Facilitating collaborative design	[426], [521]
Incorporating into architecture frameworks	[108], [129], [522]–[524]
Policy and scenario analysis	[218]
Industry Instances	**Selected References**
Aerospace	[13], [15], [75], [126], [215], [216], [395], [432], [433], [479], [525], [526]
Automotive	[13], [120], [123], [441], [475], [477], [527], [528]
Construction	[13], [115], [119], [138], [151], [156], [157], [179], [184], [203], [204], [210], [274], [423], [434], [448], [454], [456]–[458], [465], [467], [529]–[534]
Electronics	[13], [143], [276], [395], [473], [480], [535]
Energy	[453], [462], [536]–[538]
Government agencies	[522]–[524]
Healthcare	[539]
Information systems and technologies	[425]
Manufacturing systems	[127], [213], [443], [517], [540]
Mechanical equipment and components	[189], [420], [445], [449], [488], [541]
Military	[542]
Naval ship design and development	[188], [492], [519]
Network system control	[269]
Pharmaceutical	[13]
Real estate development	[543]
Software development	[117], [198], [421], [502], [514], [544], [545]

variation and risk in each. The model accounted for rework risk (probability and impact), learning curves, and, for a given work policy, the effects of alternative process architectures. It confirmed that processes can be sped up with appropriate increase in overlapping and iteration—i.e., that the process architecture with the fewest feedback marks in the DSM is not necessary optimal. Thus, the basic heuristic used to initially sequence many process DSMs, minimizing feedback marks, does not guarantee the best process. Many other DSM simulations followed, some including extensions such as resource constraints (e.g., [162]), some accounting for technical performance characteristics in addition to duration and cost [127], [161], and some focusing on other objectives such as process robustness [128]. Still other efforts have used evolutionary algorithms such as simulated annealing or genetic algorithms, sometimes employing a simulation-based fitness function, to minimize the project duration by manipulating the process architecture or other characteristics (e.g., [133], [163]–[167]). Meier [168] and Wang *et al.* [169] developed multiobjective genetic algorithms to explore time–cost optimization and tradeoffs. (Note that the evolutionary algorithms for sequencing process DSMs employ different fitness functions and techniques than those mentioned in Section II-A3 for clustering product DSMs. These two streams of the literature could benefit from further interaction and "crossover.")

Other analyses of process DSMs have applied further methods and objectives. Some have used the work transformation matrix model of fully parallel activities [159], [170]–[172] to explore process convergence (or lack thereof) and expose the phenomenon of "design churn" [173], wherein work on project activities fails to yield useful progress. Others (e.g., [174], [175]) have calculated network analysis metrics such as density, centrality, and brokerage to identify activities, dependencies, or groupings thereof expected to be of special interest. Since an earlier DSM review [12] suggested the possibility of applying clustering analysis (usually applied to static DSMs) to process DSMs, several have done so, especially within coupled blocks (e.g., [137], [150], [176]–[178]), to suggest subgroupings of activities that would foster process modularity and facilitate their assignment to suppliers [179], [180], to identify subnetworks requiring particular combinations of knowledge or skills [181], or to facilitate the scheduling of collaborative tasks [182]. Still others (e.g., [112], [155], [183]–[186]) have modeled engineering design projects at a relatively detailed level using parameter-based DSMs [12], where each node is a design parameter and the objective is to sequence their determination, like solving a system of equations. Some (e.g., [162], [187]–[191]) have considered resource constraints in the DSM-based process models and, thereby, produced insights about the comparative effects of iteration and resource challenges. Finally, in a rich model of process cost and duration that accounts for architecture, iteration, crashing, and overlapping—including a six-layer DSM that accounts for activity attributes such as minimal and maximal overlapping—Meier *et al.* [148] demonstrated that work policy decisions play a large role in project outcomes. Aside from application area or objective, several have combined process DSM models with other methods such as: axiomatic design (e.g., [139], [192], [193]), system dynamics (e.g., [123], [145], [188], [194], [195]), Petri nets (e.g., [153], [196], [197]), IDEF0 (e.g., [198]), Markov models (e.g., [158], [165]), or QFD [111], [112], [120]. (Although in many cases these supplemental modeling techniques are brought to bear due to some perceived shortcoming in the DSM, it is important to reiterate that *none* of these modeling views alone is sufficient to capture a rich process model in its entirety [108].)

4) Otherwise Benefiting From Process DSMs: Table IIIb summarizes some additional applications of process DSMs outside the mainstream focus on structuring and estimating a given project process. Several researchers (e.g., [142], [180], [199]–[201]) have used the process DSM (rather than the org DSM) to guide organization and/or supplier network design. Other uses include: predicting the effects of design or requirements changes [202]–[205], evaluating process improvements [206]–[208], prioritizing activities [209], identifying disconnects in a process flow model [15], [210], situating testing activities at appropriate places in a process [193], [211], monitoring project progress [212], analyzing resource dependencies across projects in a portfolio [187], and managing resources and/or scheduling in a manufacturing system (e.g., [213], [214]). Lévárdy and Browning [127] used a DSM to model a process as a *complex adaptive system*, where the activities self-organize according to simple rules. Early on at NASA and Boeing [77], [215], and more recently in China [216], [217], aerospace and naval researchers have harnessed the DSM to model information flows among design tools as a step toward integrating the tools into a "meta-tool" to accelerate MDO (cf., Section II-A4). Arcade *et al.* [218] sequenced a square matrix they called a "structural analysis matrix" to analyze approaches and scenarios for government policies. The process DSM has also been applied across many industries, especially the construction industry, as exhibited in Table IIIb. Again, these instances represent only ones reported in the literature—only "the tip of the iceberg" since most industry applications go unpublished. (Applications of process DSMs to software product architectures are addressed in Section III.)

Despite the wealth of applications and concerns addressed so far with the process DSM, many more opportunities exist. For example, almost all applications to date have focused on project processes, where the aim is to complete each activity once (albeit with potential rework and iterations) and finish the project. However, the process DSM might also find interesting applications in the realm of repetitive business and production processes such as assembly lines, where all of the activities are ongoing simultaneously, to explore flows, identify bottlenecks, and calculate metrics such as capacity, throughput time, and work-in-process inventory. The process DSM could also be more directly integrated with risk management, where planned risk responses could be added to a project's process DSM, thereby adding cost and duration but reducing the probability and impact of feedbacks; DSM analysis could determine the net benefit of the result and the optimum amount of such risk mitigation. Finally, despite the appearance of several papers on iteration, rework, and the process DSM in project management journals, these topics have not yet gained wide traction in the project management community—e.g., they are not yet addressed in official project management standards (e.g., [219]). Therefore, it seems that further visibility of process DSM methods and applications is needed in project management.

III. Beyond Product, Process, and Org DSMs

Beyond the older product, process, and org DSMs, several other DSM applications have recently emerged. One of these new areas, analyzing software product architectures as processes, spans the domains of product and process DSMs. Software is a product, and its architecture has been modeled along similar lines as hardware products and analyzed for patterns such as modularity using clustering algorithms, as noted in Section II-A. However, software runs in real time like a process. Therefore, it is also insightful to apply sequencing algorithms and explore the implications of architectural patterns such as cycles. Sangal *et al.* [26] took this approach and noted the importance of hierarchical levels (layers) and cycles in software architectures. Bergel *et al.* [220] extended the DSM representation to account for varied types of software component dependencies and to highlight nested cycles. Sosa *et al.* [221] found that cyclicality is at least as significant to software quality as is modularity. Both static and temporal DSM models present many opportunities to investigate software architectures.

In addition to the product, process, and organization architectures, a project's architecture includes the *tools* and *goals* architectures [222]. DSM applications have only recently begun to touch these areas, which offer very promising opportunities for future research. The domain of *tools* concerns the various nonhuman resources, facilities, equipment, and software used to accomplish work. Of special concern in this domain is the network of software applications and databases used by people and teams (in the organization domain) to accomplish activities (in the process domain) and store information. These software tools must exchange information for a project to proceed efficiently, but many times the tools do not easily interface. Some MDO applications (q.v. Sections II-A4 and II-C4) have touched on this area because MDO requires integrating the tools used by each discipline. Beyond the individual project level, the tools architecture also relates to what the information systems literature terms the "enterprise architecture." Lagerström *et al.* [223] examine the overall structure of a portfolio of 192

TABLE IV
DMM APPLICATION AREAS, WITH SELECTED REFERENCES

Domains	Selected References
(Product) Function-Component	[13], [32]–[34], [37], [248]–[250], [546], [547]
(Product/Goal) Function-(Process) Parameter	[20], [34], [251]–[259], [548]
Product-Goals	[34], [260]–[262], [264], [402], [547], [549]
Process-Goals	[263], [550]
Product-Organization	[248], [266], [267]
Process-Organization	[191], [268]–[274], [550]
Product-Process	[34], [113], [165], [275], [276], [551]–[553]
Product-Process-Organization	[277]–[279]
Process-Tools	[224], [280]
(Process) Activities-Deliverables	[20]
Organization subdomains	[13], [281]

software applications. Although only one other DSM paper [224] has addressed tools, both static and temporal DSM models offer promising possibilities for visualizing, analyzing, and improving the tools architecture.

The *goals* domain includes a project's requirements, objectives, targets, and/or constraints. Such elements relate to each other in various ways, such as when improvement toward one requirement causes a tradeoff with detrimental effects on another. This network of goals has an architecture that can be modeled with a DSM [225]. Most applications to date have built and analyzed DSM models of requirements (e.g., [226]), such as for analyses of change propagation [227], [228], or functional requirements clustering [229]. Lee *et al.* [230] mix goal and use-case DSMs in a large matrix (really an MDM) to facilitate requirements traceability and change management. Future opportunities exist to explore requirements modularity and cyclicality using static and temporal DSMs, respectively.

DSM models have also been employed in some other interesting ways. Eelman and Föller [231] used the DSM to drive scenario generation. Several researchers built DSM models of project risks to show the relationships among them and determine the second-order risks emerging from risk interactions [232]–[237]. Stamelos [238] modeled relationships among software development malpractices. Kornish and Ulrich [239] clustered a static DSM to identify opportunities for innovation. Farsad and Malaek [240] clustered a DSM model of aircraft flights to facilitate air traffic control. Unlike the change propagation models discussed in Section II-A3, Shankar *et al.* [241] used a DSM to represent the relationships among the engineering and manufacturing changes themselves, thereby studying the sources and implications of changes. Wyatt *et al.* [242] use the DSM as the basis for an economical graph encoding scheme. DSMs have even been harnessed in literature surveys: Hamraz *et al.* [243] employed a temporal DSM to model citations among publications and a static DSM to show citations across categories of literature. DSM models are becoming useful for explorations of sociotechnical systems, such as in Vaishnav *et al.*'s [244] study of cyberspace components and international relations. DSMs also hold promise for applications to portfolio management [245], data science, and many other kinds of network modeling.

IV. CROSS-DOMAIN APPLICATIONS WITH DMMS

So far we have focused on DSMs within individual domains, but many applications, such as a need to show the organizational unit responsible for each activity in a process, transcend a single domain. A simple way to convey basic relationships of this type is to use a "1.5 domain DSM" [13]—a single-domain DSM augmented with colors (as in Fig. 1), numbers, or symbols to signify relationships to another domain—such as a process DSM with each activity colored by its responsible organizational unit (e.g., [246]). For richer models across domains, a single DSM usually will not suffice. Whereas a DSM is always a square matrix, rectangular matrices have long been used to map relationships across domains. In 2004, Danilovic and Browning [222] dubbed such matrices DMMs and proposed a "periodic table" of then existing and potential DMM models across five project domains: Product, process, organization, tools, and goals. Table IV summarizes the DMM applications in our survey, which cover the most of this "periodic table." While not delineated by industry in Table IV, these applications span aerospace, automotive, consumer products, control systems, electronics, energy, marine engines, mechanical components and equipment, printing, and software.

The product domain contains at least two prominent subdomains, functions and components. Most of the product DSM applications discussed in Section II-A model components, although some model functions. Both subdomains matter, as does their relationship. The appropriate allocation of functions to components is a salient aspect of effective design—e.g., precipitating the "design matrix" of Axiomatic Design [247]. Several researchers have used the DMM to model and explore function-to-component relationships (e.g., [32], [37], [248]–[250]). As with many DMMs, the function–component DMM can be used to generate both DSMs: multiplying this DMM by its transpose yields either the function–function or component–component DSM, depending on the order of operations. Bonjour *et al.* [33] used this approach to derive a component DSM, which they then compared to a component DSM built through traditional methods. Danilovic and Browning [222] proposed additional product subdomain DMMs, and further research is still needed to ground these in the engineering design literature and in relation to each other.

Interesting relationships exist among the product, process, and goal domains. Several have mapped product functions to design parameters [20], [251]–[253], in one case performing a clustering analysis on this DMM [254]. Required, desirable, and undesirable product functions bear much in common with the goals domain (discussed in Section III): future research should explore this connection more explicitly. As such, others have mapped functional requirements (goals) to design parameters (using the nomenclature of the "design matrix" of Axiomatic Design), using this DMM to derive a parameter-based DSM [255], [256]. The DMM of customer needs to design parameters is essentially a QFD matrix [257]. Other related work includes mapping design parameters to "criteria" (essentially requirements) [258], [259]—a kind of process-goals DMM. Some have used more explicit mappings between the product (components) and goals (requirements) domains (e.g., [260]–[262]) or between the process (activities) and goals (key product attributes) [263]. Kreimeyer *et al.* [264] mapped components to load cases, which might be considered as requirements scenarios. Again, further exploration and standardization within and across the product, process, and goal domains is needed to clarify terminology and models. This will enable such models to better support the pursuit of interesting research questions, such as ones pertaining to the constraints imposed by one domain on others, or the precedence or priority of domains.

Relationships among the product, process, and organization domains gained earlier attention [12], [265], and Section II-B4 noted the studies of alignment between product and organization architectures. Whereas those studies compared the DSMs from each domain, others [248], [266], [267] have used DMMs to explore the relationships between these domains—e.g., mapping departments, teams, or people to product components and/or functions. Process-organization interdomain implications have received attention from several researchers [191], [268]–[272] who have mapped people, skills, or other resources to activities or parameters and used these models to allocate resources and determine organization structures, often via a clustering analysis. Such mappings can take the form of the conventional "responsible-accountable-consult-inform" chart from project management (e.g., [273], [274]). Meanwhile, product–process relationships have prompted modelers to map functions or components to activities for purposes of risk management (e.g., [275]), derivation of a process DSM (e.g., [276]), insight into the implications of component standardization and modularization on the design process [165], and design for manufacturing and assembly [34]. A few studies have considered the product, process, and organization domains at once to explore the propagation of engineering changes [277], the design of core competences [278], or simultaneous optimization across domains [279]. Many opportunities exist for further studies of the product, process, and organization domains and their interactive implications. One key area is the dynamics, coevolution, and emergence of these domains with respect to each other.

A few other interdomain studies have used other DMMs. With the exception of [224], the interaction of the tools domain with other project domains has received little attention but deserves much more. As the tools domain includes nonhuman resources, resource allocation or utilization matrices fall into the category of process-tool DMMs (e.g., [280]). Mapping models have also been developed within the process domain between activities and deliverables [20] and within the organization domain between people and knowledge areas [281] and between people and team assignments [13].

V. Multidomain Matrices

The importance of modeling both inter- and intradomain relationships simultaneously led to the advent of MDMs. An MDM could take the form of Danilovic and Browning's [222] "periodic table," an integration of various DSMs and their intervening DMMs. Maurer [282], [283] codified the term MDM, which gained traction in the DSM community and the literature [13]. Concurrently, Bartolomei [95] developed the "engineering systems matrix" model along similar lines. Recently, several applications have emerged that combine DSMs and DMMs in various ways. All such applications are grouped here into the category of MDMs, even if they are not explicitly aggregated into a single matrix.

From the outset, MDM models have been used to help build and verify DSMs and DMMs. For example, Sosa [284] used a product (component) DSM and a product org (component-to-person) DMM to derive an org DSM of potential interactions for comparison with an org DSM built through traditional means—thus enabling a comparison of predicted and actual communications in software development. Senthilkumar and Varghese [115] used product and org DSMs to derive a process DSM in the construction industry.

Other MDM applications have explored and supported change propagation, knowledge management, engineering design, and manufacturing systems. Because the implications of design or engineering changes reach across the product, process, and organizational domains, several have used MDM models to investigate change propagation [285]–[290]. Rich MDM models have provided a basis for capturing and storing system-level knowledge about products, design tasks, design organizations, etc. [291] and for identifying organizational core competencies [278]. In design projects, MDM models have helped to manage: design decisions [121], design communication [292], [293], product architecture risk [294], design to cost [295], product variant management [296], nonlinear system dynamics [297], causes and effects of testing failures [298], and product-organization alignment to increase development capabilities [299]. Westermeier *et al.* [300] used an MDM to model quality concerns in a lithium-ion battery manufacturing system. Kasperek *et al.* [301] used an MDM as a basis for system dynamics modeling. Eppinger and Browning [13] included several other interesting MDM application examples, such as airport security [302].

MDM research is still in its infancy with many researchers trying a variety of applications. Much recent work in the DSM research community has focused on MDM models, yet many opportunities exist to further codify and standardize MDM terminology and methods, categorize application areas, and develop analysis techniques. Although clustering and sequencing have been used with DSMs, and clustering with DMMs, it remains unclear how best to analyze an MDM containing a mix of static and temporal DSMs. MDMs also hold great promise for the emerging fields of "big data," data science, and analytics. For example, huge DSMs can capture relationships among large groups of people, and DMMs can map those people onto other domains, such as organizational memberships, product and service preferences, and purchasing habits. Analyzing all of this information in tandem reveals patterns, clusters, cycles, segments, associations, "hot spots," etc. Soon it would be appropriate to dedicate a literature review specifically to MDMs.

TABLE V
NUMBER OF IDENTIFIED DSM/DMM/MDM PAPERS APPEARING IN JOURNALS (WITH A MINIMUM OF FIVE)

Journal (Abbreviation)	Papers
Journal of Engineering Design (JED)	35
Concurrent Engineering (CERA)	28
Journal of Mechanical Design (JMD)	26
IEEE Transactions on Engineering Management (IEEE-TEM)	24
Systems Engineering (SE)	22
Research in Engineering Design (RED)	21
Journal of Modern Project Management (JMPM)	17
Computer Integrated Manufacturing Systems (in Chinese) *(CIMS)*	16
International Journal of Production Research (IJPR)	11
International Journal of Advanced Manufacturing Technology (IJAMT)	9
Management Science (MS)	9
International Journal of Project Management (IJPM)	8
Computers & Industrial Engineering (CIE)	7
International Journal of Product Development (IJPD)	7
IEEE Transactions on Systems, Man, and Cybernetics (IEEE-SMC)	6
Advanced Engineering Informatics (AEI)	5
Automation in Construction (AC)	5
Journal of Construction Engineering & Management (JCEM)	5

VI. CONCLUSION AND OUTLOOK

The outlook for DSM, DMM, and MDM modeling is bright. Perhaps the fundamental challenges at this point are the large amount of new data required to build a rich structural model of some systems, and the absence of a versatile and user-friendly software toolset for DSM/DMM/MDM modeling, manipulation, and analysis. Several promising tools have emerged in the last decade, but further work is needed to broaden their applicability and capabilities. As for the data challenge, this is not a DSM problem but rather a general problem for any system model: gathering new data is a tedious and error-prone endeavor. Fortunately, researchers are developing new capabilities to extract data from other sources to build system models rapidly. Further work is also needed to broaden the understanding, acceptance, and adoption of DSM into the mainstream methods of project management (despite some prior visibility in the construction industry). DSM has already achieved such goals in the areas of engineering design, systems engineering, and management/organization science, although even broader awareness and understanding would be beneficial in those areas as well. DSM is starting to appear in some textbooks and industry standards. Relative to some other models in operations and technology management, DSM models have received more extensive verification and validation thanks to a broad range of applications across a variety of industries, products, projects, organizations, situations, and contexts.

To provide an overview of where DSM papers have appeared in the literature, Table V counts DSM, DMM, and MDM papers in journals with a minimum of five such papers. Out of the 521 journal papers identified and acquired for this study (plus pre-2001), DSM has had the strongest presence in engineering design (*JED*, *JMD*, *RED*), engineering management (*CERA*, *IEEE-TEM*), and systems engineering (SE) journals. DSM has also established a firm foundation among Chinese researchers (e.g., *CIMS*). *JMPM* recently published a special issue with 15 short papers from the 2014 DSM conference.

This paper has provided a survey of the DSM, DMM, and MDM literature, highlighting developments, extensions, and innovations with respect to building, displaying, analyzing, and applying these models. Throughout the exposition, this paper has noted numerous opportunities for further research. In summarizing many of these, broadly, special emphasis should be put on the following applications and developments: knowledge management (where DSM/DMM/MDM provide the organizing structure for a knowledge base), architectural patterns and their implications (e.g., for quality, performance, etc.), versatile "sandbox" tools for systems architects, MDM analysis methods, multiobjective clustering, architectural metrics, and archiving rich datasets for multipurpose research applications (e.g., to test new optimization algorithms). In pursuing these opportunities, researchers should continue to draw upon the advances in closely-related areas such as graph theory, network analysis, complexity, and other types of architectural models.

ACKNOWLEDGMENT

The author would like to thank numerous colleagues in the DSM community and beyond for countless discussions and insights, and also L. Dai, A. Riabinina, and F. Guo for providing excellent research assistance.

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Tyson R. Browning received the B.S. degree in engineering physics from Abilene Christian University, Abilene, TX, USA, in 1993, two S.M. degrees in aeronautics and astronautics and technology and policy, both in 1996, and the Ph.D. degree in technology, management, and policy, in 1999, from the Massachusetts Institute of Technology (MIT), Cambridge, MA, USA.

He is currently a Professor of Operations Management with the Neeley School of Business, Texas Christian University (TCU), Fort Worth, TX, where he conducts research on managing complex projects and teaches MBA courses on project management, operations management, risk management, and process improvement. He has served as a consultant for several organizations and has prior work experience with Lockheed Martin and Honeywell. His research papers have appeared in the IEEE TRANSACTIONS ON ENGINEERING MANAGEMENT, the *Journal of Operations Management*, *Manufacturing and Service Operations Management*, *Production and Operations Management*, and other journals. He is a co-author of a book on the design structure matrix.

Dr. Browning serves as a Department Editor for the IEEE TRANSACTIONS ON ENGINEERING MANAGEMENT, an Associate Editor for *Systems Engineering*, and is on the Editorial Board for the *Journal of Operations Management*.