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BIM Steering Force

Devising a Data-Driven Approach to Identify Key Factors to Promote Cooperative BIM in Large-Scale Projects

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Dissertation Abstract — Academic Year 2021

BIM Steering Force — Devising a Data-Driven Approach to Identify Key Factors to Promote Cooperative BIM in Large-Scale Projects

Stagnant productivity and workforce shortage are global problems in the Architecture, Engineering and Construction (AEC) industry. Particularly in Japan, slow digital transformation causes lag in leveraging technologies. Building Information Modeling (BIM), a novel digital platform internationally spreading, is expected to enhance productivity. Still, its implementation and collaboration in practice have remained major issues for the last decade. The research question of the thesis is threefold. First, how can a layperson decipher the BIM activity in a data-driven manner? Second, what are the traits of BIM activities in large-scale projects? Last, how can the key BIM cooperator in collaborative projects be specified? The literature review revealed that BIM log mining, a machine-learning-based process mining method, is an emerging and plausible approach. Preparatory studies discovered that outsourcing the modeling workforce could rather disengage project architects from the activities executed in BIM. The proposed methodology introduced visual analytics to assess the result for laypersons. Three different datasets comprise extensive and multidisciplinary BIM records collected from a broad range of organizations, including supplemental big data to overcome the drawbacks of the existing methods. The classification process and visualization are incrementally tested through the empirical chapters. The devised method identified a group of collaborative BIM users in the corporation despite considerable dependence on external BIM workforce termed as BIM operators. Those players can be interpreted as keystone species in the corporate BIM environment. The interview further revealed that mutual respect motivates practitioners for successful BIM learning. The proposed BIM log mining approach is novel, versatile, and comprehensive; different datasets proved its utility. The thesis recommends BIM education aiming for such cooperative BIM practitioners and further research on BIM operators for more successful interpretation to the local ecosystem.

KEYWORDS: *BIM log mining, visual analytics, semi-structured interview, keystone species, Japanese general contractors, large-scale projects*

Tsukasa Ishizawa

博士論文要旨 — 2021年度

BIMの推進力 – 大規模プロジェクトの協業的なBIM推進に寄与するデータドリブンな解析手法の開発

BIM（Building Information Modeling）は国際的に普及しつつある新しいデジタルプラットフォームで、建設業の生産性向上やデジタルトランスフォーメーションに寄与することが期待されている。しかしその複雑性や高い教育コストから、導入や実務での連携に課題が多く、特に日本で導入の遅れが目立つ。日本の建築・建設業は大工棟梁の時代の商習慣を受け継いでおり、西洋的な垂直分業を前提とした環境を導入するためには相応の解釈が求められるはずである。実態としてはBIMに関する諸作業は専門人材や外部人材に外注されており、BIM導入がむしろ作業実態の空洞化を招いている懸念がある。本論文はBIMの普及に貢献するため、実際のBIM活用プロジェクトにおける実務者の行動を解析し、成功に導く鍵を握る人物像を描出することを目的とする。第一に、BIM上での様々な活動を視覚的に共有する手法を開発する。プロセスマイニングの応用と、ビジュアルアナリティクスの導入が技術的な鍵となる。第二に、その手法を多数の国や組織から収集したデータに適用し、大規模プロジェクトにおけるBIM活動の特徴を抽出する。第三に、日本の大手総合請負業（ゼネコン）から収集したデータを解析し、プロジェクトに貢献する人物を特定し、インタビューを通じて検証する。結果、協業的なプロジェクトでは、一部の社員が適切なレベルのBIMの知識を獲得しており、その学習は外部人材に敬意を払い対等な関係を構築することが動機となっていることがわかった。本研究で開発したBIMログ解析手法は、直観的であるため背景知識を必要とせず、既往の手法より分野横断的な分析に優れ、多種多様であるプロジェクトの状況に応じて解析を行えるという有用性がある。水平分業を前提とした協調的な日本の建設業において、BIMはコミュニケーションツールとしての実用性が強く問われる。本論文は、上記の如き協力的なBIM活用を可能にする人物像を明らかにし、そうした職能を拡充するためのBIM教育と、建築実務の分業体制の実態に即した関係構築を可能にするさらなる研究を推奨するものである。

キーワード: BIMログ解析, ビジュアルアナリティクス, BIMオペレータ, キーストーン種, ゼネコン, 大規模プロジェクト

石澤　宰

Acknowledgement

My decision to apply for a doctoral program was sprouted from work experience abroad. Although Singapore was promoting BIM as a national policy, the formation of BIM-related professions was sporadic, and various discussions were simultaneously underway. I was in the position of BIM manager for the assigned project; despite my title of architect, as a mainstay of my expertise, it was invalid outside of Japan. I spent four years being a mere designer and a struggling practitioner in an emerging BIM field. Afterward, I entered graduate school in September 2017, intending to complete a doctoral dissertation for molding my expertise into a shape of publication.

First of all, I would like to express my sincere gratitude to the professors of my dissertation committee. Professor Yasushi Ikeda, the chief examiner and supervisor, has opened many opportunities for me in my career development since I was an undergraduate in my early twenties. He has always mentored me as an academician as well as a practitioner. His guidance was in the research field and business collaboration and establishing the Architectural Information Society of Japan. Dr. Hiroto Kobayashi, the vice-chair, motivated me to publish this dissertation in English and offered me the opportunity to work as a researcher on a project at the SFC Research Institute. Dr. Kazuya Shide's publications are among the few in Japan that focus on BIM practice, and reaching his academic level has been a critical benchmark for me. Dr. Yasuto Nakanishi shared his candid opinions at the round table discussions, which led me to many realizations that eventually formed the basis of this thesis through the book "Towards Architectural Informatics." Professor Yasushi Kiyoki, who retired while I was in this program, imparted his knowledge of semantic computing to me, who had no familiarity with data science then. His mathematical model of meaning was a decisive concept for me to incorporate visual analytics.

Next, I would like to thank the data donors for the analysis. A total of 226 data providers have participated, allowing me to discuss the largest dataset among the existing studies to date. Several of them generously agreed to complete additional surveys, including questionnaires and interviews. The results provided extremely valuable data for examining the hypotheses. Although I cannot mention individual names here due to privacy concerns, I wish to take this opportunity to thank every one of them for the immeasurable significance of their data to this study.

In addition, I would like to acknowledge those who have inspired me with insights that have greatly propelled my research. Dr. Keita Kado from Chiba University provided me with a case study of process mining and offered important suggestions on relating BIM log mining to a broader context. The idea to apply the keystone species concept was brought by the collaboration with Dr. Mizuki Oka to co-author the publication "Toward Architectural Informatics." Mr. Toru Inaba assisted me in improving a Python program I created. Mr. Soki Nakamura and Mr. Gen Sato provided important advice on applying machine learning algorithms. Ms. Nanae Matsushima taught me how to organize the data and refine the visual presentation. Mr. Takafumi Yamano lent his ear from time to time and shared extensive insights into Japanese architectural history with me. Dr. Yasin Idris has been a dear friend and my counselor throughout the Ph.D. program. His experience and warm words of encouragement have guided me through the lengthy peer-review process to this day.

This project became possible by entering a graduate course as an employed working professional. I express my heartfelt thanks to my superiors, colleagues and team members who trusted me, allowed me to study at the graduate school, and supported me in balancing my work and career despite the difficult labor management in general contractors. Also, I deeply appreciate the members of the Architectural Information Society for granting me the opportunity to expand my social network dramatically.

Finally, I would like to conclude by expressing my deepest gratitude to my family. I was fortunate enough to have two daughters during the doctoral program. My dear family has always supported me in pursuing my research in the early mornings and weekend hours. I wish to dedicate this thesis to my wife Yuriko, daughters Akari and Hannah, parents Akira and Shioji, and all other family members. I pledge to further contribute to the Japanese building and construction industry through my professional career.

9 February, 2022
Tsukasa Ishizawa

Table of Contents

Abbreviations

AEC	Architecture, Engineering and Construction
AIJ	Architectural Institute of Japan（日本建築学会）
AIS-J	Architectural Informatics Society of Japan（建築情報学会）
BEP	BIM Execution Plan
BIM	Building Information Modeling (Model | Management)
CIM	Construction Information Modeling
CAD	Computer-Aided Design
EIR	Employer’s Information Requirement
GHG	Greenhouse Gas
IFC	Industry Foundation Classes
IPD	Integrated Project Delivery
JFCC	Japan Federation of Construction Contractors（日本建設業連合会）
LoD	Level of Development (Detail)
MEP	Mechanical, Electrical and Plumbing（建築設備）
MLIT	Ministry of Land, Infrastructure, Transportation and Tourism（国土交通省）
PDF	Portable Document Format
SDGs	Sustainable Development Goals
ZEB	Zero Energy Building

List of Images

List of Tables

Chapter 1: Background

Building Information Modeling

Definition

Architecture is a fruit of collaboration. It is impossible to provide architecture today as a business without multidisciplinary cooperation. Thus, the processes in the industry always entail the transfer of information. Project communication is the means of passing a piece of information from one person to another. Building Information Modeling (BIM), the subject of this thesis, is a medium, tool, and environment for project communication.

As briefly summarized by Miettinen et al., there is no single satisfactory definition of BIM. It should be comprehended as a multidimensional, historically evolving, complex modeling method [1].

BIM is one of the most promising recent developments in architecture, engineering, and construction (AEC) [2]. It is important to note that BIM is not just software; it is a process and software. BIM means not only using three-dimensional intelligent models but also making significant changes in the workflow and project delivery processes [3]. Therefore, BIM can rather be regarded as an industry-wide working platform. The National Building Information Model Standard Project Committee in the United States (NBIMS) defines the term BIM as a business process for generating and leveraging building data to design, construct and operate the building during its lifecycle. BIM allows all stakeholders to have access to the same information at the same time through interoperability between technology platforms [4]. Figure 1 represents the 3D view from a project model.

Linked to this, often, BIM is referred to as the Building Information Model, which is the digital representation of physical and functional characteristics of a facility. Not only is the model retained as the accurate geometric information source, but also it can contain non-geometric attributes, including the required specification, selected material, name of the manufacturer or even the period of warranty. Furthermore, BIM can be interpreted as Building Information Management, which is the organization and control of the business process by utilizing the information in the digital prototype to affect the sharing of information over the entire lifecycle of an asset.

BIM in the Japanese context was first officially defined by the MLIT guideline for public projects [5]. The document defines BIM as creating a model of information of buildings on computers that includes three-dimensional geometric information and attributional data such as names and areas of rooms, specifications and performance of materials and components, and finishings, and the like. The efficient and effective use of BIM is expected to ensure quality and enhance customer satisfaction in government facilities.

Origin

The concept of using computers for architectural production can be traced back as old as the invention of early personal computers. After the invention of the first commercial numerical-control programming system in 1957, Sketchpad by Ivan Sutherland demonstrated the basic principles and feasibility of computer technical drawing in 1960. Nicholas Negroponte founded 1967 the Architecture Machine Group, where he developed an early computational simulation environment called Urban 5 that aimed to communicate with the architect-user for dialoguing [6].

The term building model parallelly understood as the concept of BIM first appeared in academic publications in 1986, in an article by Simon Ruffle [7] and another by Robert Aish [8]. The term Building Information Modeling was first brought by the article titled "Modeling multiple views on buildings" in 1992 [9].

The spread of commercial software products gained the popularity of BIM. Even though the well-recognized first BIM product Archicad was launched in 1987, the turning point was brought by the white paper issued by Autodesk named Building Information Modeling in 2002 [10], the year the company purchased Revit Technology Corporation.

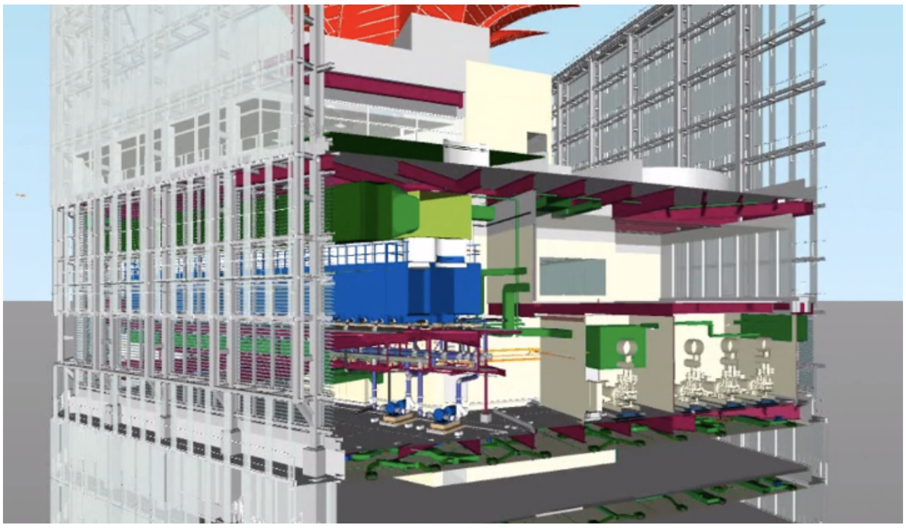

Figure 1. Sectional 3D view of coordinated project BIM model from the author's project.

BIM in Japan

MLIT announced the BIM pilot projects in 2010, namely Shinjuku Government Building for the Ministry of Labor, Fujieda Government Building for the Ministry of Justice, and Maebashi Common Building for the government office. Through the learning from projects, threefold benefits were allocated for public BIM projects. Firstly, to enhance the clarity of design understanding; secondly, to regularize the interdisciplinary coordination and attributional information; lastly, to unify the building information platform. It was expected to harvest the learnings through these trials to expedite the leverage of BIM technologies.

Afterward, the government BIM adoption is associated with the framework of i-Construction. On September 12, 2016, Prime Minister Abe's policy to aim for a 20% increase in construction site productivity by the fiscal year 2025 was presented in preparation for a "construction site productivity revolution" by the Fourth Industrial Revolution [11]. After the BIM/CIM Promotion Committee was established in 2018, the MLIT founded the Architectural BIM Promotion Council in June 2019 to promote BIM in a coordinated effort between the public and private sectors.

The council's objective was to improve productivity in the AEC field by building a framework for the consistent use of information through BIM throughout the production and facility management processes. In addition to sharing the status of studies being conducted in respective fields and presenting a future vision for the production process and the surrounding landscape, a roadmap showing the division of roles between the public and private sectors toward this vision is to be announced. To address specific tasks, the Architectural BIM Environment Development Subcommittee was launched in October 2019 to study consistent workflows [12].

Advantage of BIM

Improved consistency

Completing the building lifecycle with a consistent model is the vital concept of BIM. The model should be a single entity throughout the project phases, starting from basic design to the building handover and even facility operation and management. However, it has been a great concern in the AEC industry that the necessary project information is fragmented in huge numbers of drawing sheets with all different versions. Such a situation is rooted mainly in paper-based drawings. In addition, it is worth emphasizing that every single building is uniquely designed, engineered and built by the project team.

The magnitude of BIM implementation primarily lies in eliminating errors during the design and construction processes. The drawing-based workflow limits the discussion area to a fraction of the entire design. It frequently causes discrepant decisions with other requirements. The information is often rectified only partially, which causes the inconsistency downstream. Figure 2 depicts the conventional workflow likely to have information discrepancies.

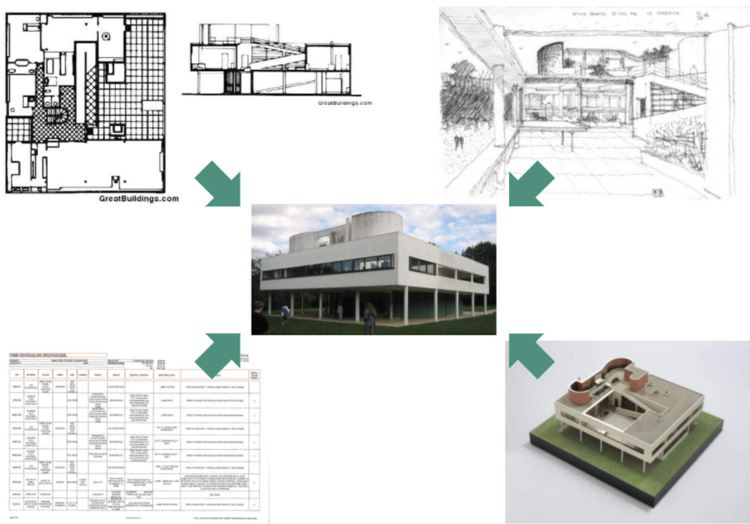

Figure 2. Concept of conventional information system in building design.

Critical success factors for implementing BIM, presented by Antwi-Afari et al., provide a longitudinal view of the effectiveness we can expect [13]. Among 34 listed factors, considerable ones are relevant to the benefit that model-based workflow eliminates the discrepancies between different architectural representations; such as accurate 3D visualization, the model for shop drawings and offsite prefabrications, verification against design intent, and accuracy and reliability of data (less reworking and fewer document errors and omissions). The concept of BIM-based streamlined workflow is conceptualized in Figure 3.

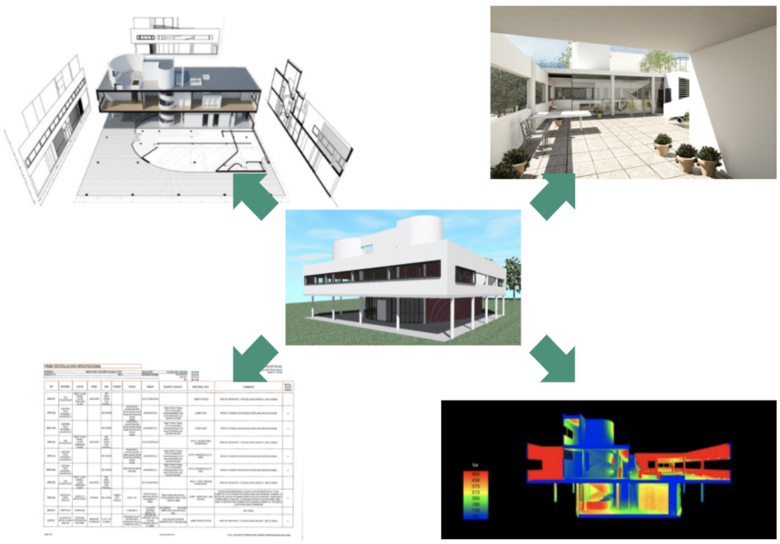

Figure 3. BIM-centric information system in building design

Effective collaboration

The large-scale development project comprises extensive requirements that no single professional can completely digest. Such building types include high-rise commercial buildings, healthcare and educational facilities, transportation terminals such as railroad stations or airports. Even including average residences, small storages or experimental pavilions, today's buildings inevitably require collaboration. More importantly, large-scale collaboration, regardless of the project scale, project price or the use of buildings, naturally requires effectiveness for the successful completion and handover.

Cooperative coordination becomes possible by the presence of experts from multiple disciplines. A typical building project involves architects, structural engineers, MEP engineers, quantity surveyors, cost estimators, construction planners, site managers and many subcontractors. Complex projects can additionally require the participation of sustainable designers, landscape designers, consultants for various services such as façade design, fire safety or building security. Because the respective software programs normally support their expertise, deliverables from individual specialists vary in the format and frequently are not interoperable. It is where the compatibility of information over BIM comes to attention.

Moreover, the building project dynamically develops along the timeline. A few project members, led by the leading architect, determine the building form and the fundamental building design upon the analysis of the site context, project requirements and many more factors to be considered. As the model proceeds along its lifecycle, BIM teams become multidisciplinary and cross-functional [14]–[17]. In such an environment, known as a big room concept [18], the individual BIM specialists update their respective models to complete the project model as a single, trusted information source for the project. These specialists are responsible for creating individual models and the model federation, clash coordination, and documentation, which occupy a considerable amount of time. Managing team performance and enhancing collaboration requires a multidimensional assessment, which is impossible to perform using the modeling-based performance monitoring systems.

Front-loaded decision making

Digital modeling is a means to achieve lean production processes. It has revolutionized the manufacturing and aerospace industries. Early adopters of the workflow and tools, such as Toyota and Boeing, have accomplished high efficiencies and successes in business [19]. As a late adopter among the industries, AEC encounters challenges that early adopters have faced.

An ordinary building project spends one to three years to complete the design phases to proceed to the construction. It sometimes prolongs years in massive and complex development, and the project team transforms alongside. Even if the team remains the same, the design information often refreshes, and the design input is built from scratch. Such loss of value in information assets across phases has been recognized, leading to errors [20]. The building information has been by no means a single source of truth. Figure 4 conceptualizes the value of information in traditional workflow and the ideal BIM-based delivery process [21].

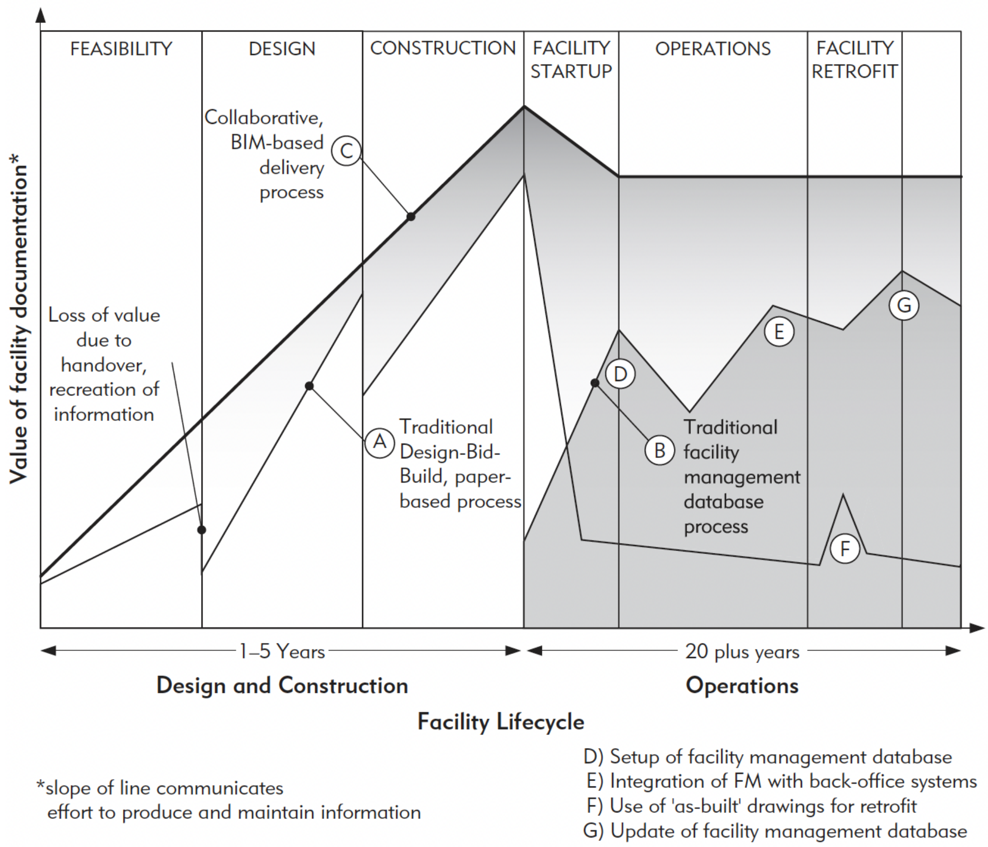

Figure 4. Facility Lifecycle comparing Collaborative BIM-based delivery process with traditional. Source:[21], copyright (2008) by the title of publisher.

The well-known diagram, often called the MacLeamy curve, suggests a new distribution of design effort under a full collaboration model, as shown in Figure 5. Line 4 in the chart becomes possible when substantial information is collected, integrated, and documented earlier in the design process due to the input and collaboration of all stakeholders. Line 1 depicts the critical concept of the earliest possible decision-making to maximize the ability to effect change and minimize the potential cost of design changes, particularly those caused by the wrongly integrated design information [22].

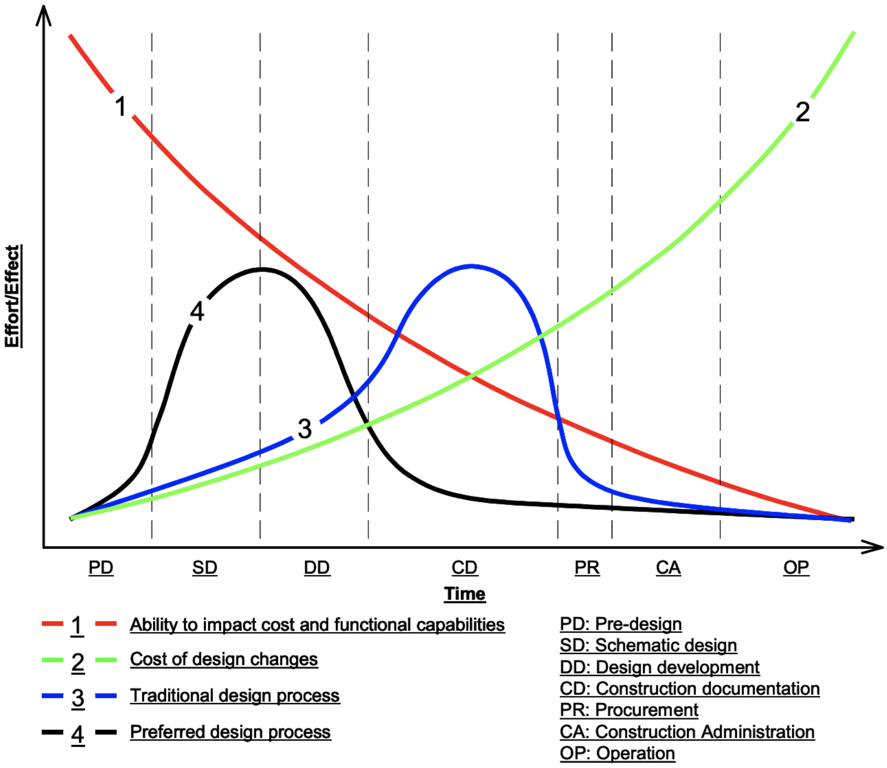

Figure 5. Relationship of design effort/cost and the traditional phases of design and construction, source: [22], copyright (2004) by the title of publisher.

BIM is expected to eliminate the informational joint loss that occurs across the phases, hindering the use of available information at its maximal potential. Rectifying conflicts that result from faulty design decisions account for 5 to 8% of total project costs [23]. A mean design error cost of 14.2% of a project's contract value has been reported [24]. Design errors occupy a notable portion of project costs, especially considering that the design process itself typically accounts for approximately 5 to 10% of the total cost [20]. As a result, the cost of rectifying design errors is nearly the same magnitude as the modeling process in the design phase. Eliminating the unwanted expenditure for the project is hard to achieve, yet the elementary step for raising the development's profitability.

Connection to digital technologies

The availability of BIM models enables the application of state-of-the-art digital technologies, which potentially revolutionize the design and production processes. The expanded possibility of model-based projects is outlined in Figure 6. Herein, three major technologies whose utility is actively discussed in the academic society are introduced.

Three-dimensional printing, often called additive manufacturing or layered production, enables the direct production of designed geometry. The technology can potentially simplify key processes in the facility lifecycle, for example, by the following design to production principles and reducing waste while increasing the quality of the final product [25]. Various 3D printers with a range of printing sizes and materials realized novel approaches in design and construction phases, including rapid prototyping in the design stage, virtual mock-ups, building component production, or even printing the entire house [26]–[29].

Three-dimensional scanning brings real objects into the digital environment. Two major approaches are laser scanning, which represents the acquired data by point clouds, and photogrammetry, which creates a mesh from a series of picture images. The most significant effect of the technology is to capture the as-built condition that allows the highly precise planning against the accurate existing conditions (scan-vs-BIM). The advanced method turns scanned data into digital components that can be directly navigated or modified, even often accompanied with enriched semantics (scan-to-BIM) [30]–[34].

Extended Reality (XR) is an umbrella term that rolls together similar acronyms such as VR (virtual reality), AR (augmented reality), and MR (mixed reality). Those technologies that simulate a construction project in a multi-dimensional digital model and present multiple aspects can be a tremendous help in all stages. The immersive experience shared among the project stakeholders enhances common understanding. It contributes to front-loading the decision-making by non-professionals, enables real-time conversation in digital space, often called telexistence, and supports educational programs [35]–[40].

Figure 6. Connection to broader innovative digital technologies from BIM.

Non-geometric information (nD BIM)

The digital transformation of building design and production began as a concept in the middle of the 1960s [41]. Raising a digitally-assembled building as “digital twins” of architecture became possible by the emergence of BIM [42]. Because the visualization that 3D BIM brought was not enough to achieve faster delivery, many other dimensions were sought to be incorporated as the attributional information of BIM components added for BIM to maximize its potential.

These activities linked with the 3D BIM model lead to some n-dimensional extensions, recently proposed in the literature. The nD model is an extension of the 3D BIM model that added multi-aspects of design information required at each stage of the lifecycle of a building facility. While the clear agreement is presented to regard the time factor as the fourth dimension, followed by the cost aspect as the fifth, only vague understanding is shared with 6D for sustainability and 7D for facilities management. Following the recommendation in [43] up to 5D BIM, this thesis, in principle, adopts the term BIM for sustainability instead of 6D BIM and BIM for FM (7D) to avoid confusion.

4D BIM incorporates scheduling information to model construction sequences, which better visualize how the construction will be sequenced. Conventional protocol for the construction program in Gantt chart or network diagram still occupies the main position in professional communication though, the phased construction diagrams or animation presentation superior to the traditional presentation in the clearer understanding among the site workers, construction managers and project stakeholders [44]–[47].

5D BIM is generally considered to be adding cost information to a model. It presents itself as a potential solution to the problem and a tool allowing better and more efficient cost management. When the 3D models are accurate enough, quantity take-off may be conducted by analyzing the component geometry. Multiplying the unit price to the obtained quantities should automatically lead to the cost for the relevant items. Despite its theoretical possibility, concerns exist to achieve the full-scale building price such as the non-modeled objects, temporary works, model accuracy and profitability. Nevertheless, multiple studies are made to derive the merit for the financial aspect of projects [48]–[51].

BIM for sustainability (6D, often 7D) refers to analyzing the energy consumption and environmental performance that offers energy estimates from the early design stage. The ability to analyze and evaluate green performance against the rating system and the presentation to make sustainable decisions are expected throughout the design and construction [52]–[54]. The background for the necessity will be separately explained in the later section.

The quality of information entered by project teams can benefit the facility management after the building completion. BIM for FM (7D, often 6D) is a concept that assumes the continual use of BIM even after the design and construction process is over. BS EN ISO 19650-2, the most widely recognized standard for BIM, regulates that Construction Operations Building Information Exchange (COBie), a non-proprietary data format for the publication, should be used to structure the non-geometric data. The coverage of nD BIM in each dimensionality shows a substantial unevenness as seen above, and the area of facility management, including the building operation, could be as broad as, or even broader than, the building and construction field. Still, several studies are in progress to mitigate the pain in the mainstream workflow generally lagging far behind digitization [55]–[59].

Industrial Need for BIM

Continuous urbanization and increasing building demand

Japan's population has entered into a phase of decline. Japan's total population peaked in 2008 at 128.08 million, and since then, it has been consistently falling [60]. Future projections by the National Institute of Population and Social Security Research predicted that the population will decrease to 92.8 million by 2060. Nonetheless, in the long term, construction investment in Japan is expected to remain at about the same level until 2030. The Research Institute of Construction and Economy predicts that construction investment, which was 65.4 trillion yen in 2019, declined in 2020 due to the pandemic, yet it will recover to 64 trillion yen by 2030 in the most realistic scenario and retain the equivalent level for the next five years [61]. In the private non-residential sector, this is due to structural changes in each industry being reflected in construction expenditure as a mainstay of capital investment. In contrast, in the residential sector, the population concentration in the capital and the enhancement of the secondhand property market and the growth of the renewal market are expected to substitute the current state partially.

Although the Japanese construction market derives most of its profits from the domestic market, expansion overseas has been increasing on average over the past few decades. The Overseas Construction Association in Japan (OCAJI) issues their outline of overseas contracts annually, in which, despite the sharp drop of the total value of signed contracts in 2020 under the COVID-19 situation, the overall trend shown since 1991 has been steadily growing. Against the backdrop of the continuous global urbanization predicted by the United Nations [62], the revenue from the international projects is not foreseen to shrink. Overall, the building demand will maintain or even slightly increase until the middle of this century; the AEC industry is challenged to meet this social requirement.

Stagnant productivity and foreseen labor shortage

The productivity growth in the construction industry internationally has been stagnant for decades [63]. The index between 1990 to 2005 showed little growth in the states and France or even negative trends in Germany and Japan [64]. In the case of Japan, the decrease of construction workers has been happening more rapidly than the shrinking of its total population. The government statistics predict a shortfall of 470,000 to 930,000 construction workers by 2025 [65]. The aging workforce accounts for the principal factor. Thirty-five percent of the labor pool is over 55 years old in 2019, while less than 11 percent is under 30. The cohort has stayed older than the all-industry average, with the retiring population outnumbering the new entrants [66].

After the revolution in the AEC industry happened during the rapid economic growth after World War II, it is highly challenging to identify room for improvement in construction productivity. Even worse, the experienced workforce has reached retirement age, which further complicates sustaining productivity and quality assurance [67].

The Ministry of Land, Infrastructure, Transport and Tourism (MLIT) has been striving to overcome the situation by reducing overtime, providing subsidies to employers, and reviewing the insurance system [68]. On top of these, the utilization of Building Information Modeling (BIM) is imperative for improving overall productivity. Extensive countermeasures to raise construction productivity have been considered, invented and implemented by the industry players to date. Standardization, unitization, prefabrication and pre-assembling have been the most practiced approaches since the middle of the last century. The BIM facilitates the introduction of the standard and unitized building parts once the suppliers make the relevant model available.

Climate crisis and responsibility of the industry

Increasing demand for greener or more environmentally efficient buildings has helped increase demand for integrating BIM into design processes [69].

Offsetting carbon emission is an urgent global concern. The Intergovernmental Panel on Climate Change (IPCC) concluded that urgent action is called to suppress the global warmth within two degrees [70]. Among the greenhouse gas (GHG) emissions by the economic sector, the building and construction industry is responsible or at least highly influential to electricity and heat production (25%), buildings (6%), transportation (14%) and industry(21%). Therefore, the AEC professionals are relevant to more than 65% of the human activities that lead to the climate crisis. The building and construction activity actions have tremendous impact and responsibility to achieve the Sustainable Development Goals (SDGs).

Net Zero Energy building (NZE), commonly termed as Zero Energy Building, Japan (ZEB) in Japan, is the building or development that generates as much energy on-site as it consumes. ZEB is an integrated solution to address energy-saving, environmental protection, and GHG emission reduction in the building sector. ZEB could even be possible with electricity production if enough renewable energy could be used. Moreover, various building-service systems with renewable energy sources have been widely considered for potential applications in ZEB [71]. Globally the governments started to mandate the achievement of ZEB to standardize it for the next average in coming decades. The Japanese government targets to achieve the average net-zero carbon emission by 2030 in non-residential buildings. Architecture 2030 is a non-profit organization established in 2002, which aims to rapidly transform the built environment from the major contributor of GHG emissions to a central part of the solution to the climate and energy crisis. The progress report issued in 2014 revealed that the third quartile of modeled projects is remarkably close to meeting the goal. The document clearly states that the only way to achieve a net-zero project is to have an energy model in place [72]. Iterative modeling and thorough energy simulation are promising approaches to accomplishing this ambitious goal.

It should be highlighted that while most BIM platforms target the global market, there exists certain unevenness for the advantage in designing environmentally high-performance projects. It is advantageous to select Autodesk Revit to fulfill the requirements from LEED (Leadership in Energy and Environmental Design), the globally used green building rating system. The considerable time savings in simulating the energy model and preparing the assessment document because Revit is tightly associated with the system of LEED. Contrary, the evaluation and documentation for Comprehensive Assessment System for Building Environmental Efficiency (CASBEE), the green building certification in Japan, is yet to be incorporated with any existing BIM applications so far.

Challenges in BIM Implementation

Smith highlighted that while the technology underpinning BIM has been around for over a decade, BIM implementation and take-up have been relatively slow in the construction industry compared to manufacturing and engineering [73]. Rather, Lee states that BIM acceptance and use remains a central concern of BIM research and practice [74]. BIM is perceived as an enormous opportunity and challenge for the construction industry.

Incomplete digital lifecycle

A 2016 McKinsey report pointed out that the construction industry is the second least digitized among 22 industries [75]. A white paper by Box, a company that offers the cloud-based content management system, clearly illustrates that the intra-organizational distribution of information in the construction industry is extremely high. The connection in a leading residential and commercial construction firm shows the dispersed connectedness among employees, few overall centralized nodes, and the high presence of parties outside the organization at each building site[76].

Some studies have found that BIM use is often abandoned in the project despite its obvious necessity. It will be partially because of the nature of the industry depicted above. The difficulty in sustaining BIM use lies on the bridge from design to construction and facility management. Eadie et al. found that BIM is most often used in the early stages of the project, such as the design and preconstruction stages (i.e., detailed design and tender stages), with use progressively diminishing with project development into later stages such as in the feasibility, construction and operation and management stages [77]. This focus on BIM in the early stages of a project is similarly found in academia. Sacks et al. highlighted that most academic and industrial research on BIM focuses on design and preconstruction planning, with significantly lower efforts to develop BIM-based tools to support coherent production management on-site [78].

As the model proceeds along its lifecycle, especially in the construction phase, BIM teams become multidisciplinary and cross-functional [14]–[17]. In such an environment, known as a big room concept [18], the individual BIM specialists update their respective models to complete the project model as a single, trusted information source for the project. These specialists are responsible for creating individual models and the model federation, clash coordination, and documentation, which occupy a considerable amount of time. Managing team performance and enhancing collaboration requires a multidimensional assessment, which is impossible to perform using the modeling-based performance monitoring systems.

Role of governments

Many countries have mandated building information modeling (BIM) in domestic building and construction projects [32]. Cheng and Lu analyzed the wide range of BIM information from 14 countries/regions and concluded that the public sector plays an essential and primary role in BIM adoption. They summarized six roles that the public sector can play for BIM adoption: initiator and driver, regulator, educator, funding agency, demonstrator, and researcher [79].

The Singapore government has been promoting the use of BIM since 2011. The chief reason for this political decision is based on the industry’s low productivity, which highly relies on the foreign workforce [81]. Since BIM is expected to be a game-changing technology to achieve continuous growth, the BIM roadmap was established to gradually gain the BIM capacity and capability nationwide [82]. The online submission system named eSubmission requires all new development projects with more than 5,000 square meters in gross floor area to submit the digital model for necessary authority clearance since 2015.

In addition to encouraging BIM in construction and subsequent stages of the project, linking BIM between design and construction is ever more seen as a critical step in completing the project BIM lifecycle. The United Kingdom includes such an outlook in its BIM strategic plan (Digital Built Britain). The Singapore government launched an implementation plan for Integrated Digital Delivery (IDD) to integrate building processes and stakeholders, including digital design, digital fabrication, digital construction, and digital asset delivery and management [83]. Raising the likelihood of maintaining the BIM initiated in the design stage to the end of the project leads to achieving the industrial goals.

After seven years had passed since then, it was reported that only two public projects adopted BIM in the design phase in 2017 by September [84]. Even considering the increment by the end of the year, public BIM projects decreased from the past three years in the design phase. The lagged progress will be further studied in the preparatory chapter, especially at the government level.

BIM in design-and-build projects

The quality of Japanese buildings is generally considered to be admired. Buntrock explains through her experience: "Japan's construction industry has consciously made different choices compared with the choices in the same industries in North America or Europe. Designers and contractors celebrate common goals in the execution of built work; aesthetic and material decisions are not solely the architect's realm. Anyone on-site may make design decisions, working under the architect's orchestration." [85]

Cooperative relationships cultivated by the historical background are the virtue of the Japanese AEC industry, and general contractors are representatives that embody the concept of such cross-disciplinary collaboration. Kajima, Shimizu, Taisei, Obayashi and Takenaka have been renowned as top five for a long time, providing inclusive and coordinated services from the research stage, followed by design, engineering, construction, and maintenance and management phases [86].

Many, often more than half, of projects the top five general contractors undertake are design and build [87] (the origin and historical background will be examined in depth at the literature review.) They provide complete building design, engineering, and construction planning and management under one big umbrella. Giant general contractors in Japan could build their BIM capability smoothly and accumulate the project know-how swiftly. On the other hand, many factors are correlated to the scheme that is likely to hinder BIM adoption. Their actual BIM workflow is often considered an internal matter of one particular entity. Despite recognizing that challenges exist, scholarly contributions are scarce for overcoming them through data-based research and recommendations [88]–[90]. As is always the case for large corporations, their size makes them unwieldy and unable to easily respond to rapidly changing circumstances. Nonetheless, resolving issues of BIM workflow within Japanese general contractors is vital not only for themselves but also for a broader audience in the whole industry.

Kaneta listed the barriers to BIM implementation in Japan as the lack of governmental activities, the absence of BIM management, and low interest by clients. He took multiple aspects representing the uniqueness of the Japanese construction industry into consideration, namely the general contractors-initiative shop drawing production, decision making in the last minutes of the project timeline, and the scarce opportunity of productivity enhancement [91].

Human resource and education

Enriching BIM talent is paramount for successfully transforming into the BIM-enabled project team. The local market can interpret the significant impact of the BIM concept and workflow as the emergence of BIM-specialist roles. The lagged BIM progress is often a result of the need for an increased BIM workforce. Globally, skilled BIM personnel are in short supply, and the increased demand has presented challenges to existing professionals. Multiple Japanese universities recently started BIM programs in architectural curricula. Many AEC firms have started to seek BIM-equipped (and economically reasonable) human resources in overseas talent, including the Philippines, Vietnam, or India.

BIM has a steep learning curve in general; the acquisition cost is considered high [92], [93]. It is unrealistic to expect everyone in the construction industry to become a BIM user capable of modeling. On the other hand, insufficient BIM knowledge poses a significant risk for project collaboration and management [94]. The practitioners should acquire a practical BIM skill balanced between creation and collaboration.

BIM educational programs mostly emphasize modeling work on the presumption that architects do most modeling operations by themselves. In actuality, however, the task of producing digital architectural data has been widely outsourced to the dedicated operator as highly specialized work since the era of 2D-CAD [95]. Even though BIM can streamline the building and construction process, it is not automatically evident that BIM enables federate tasks formerly outsourced into the in-house workflow.

The unavailability of skilled BIM personnel is frequently experienced. The dispatched workforce titled BIM operators is normally seen in projects. Figure 7 depicts a design-build general contractor's specialist deployment in a large-scale BIM project. Despite its commonality, the reality of the hollowed BIM workforce has not been dragging attention. The preparatory studies and empirical chapters will further investigate this aspect.

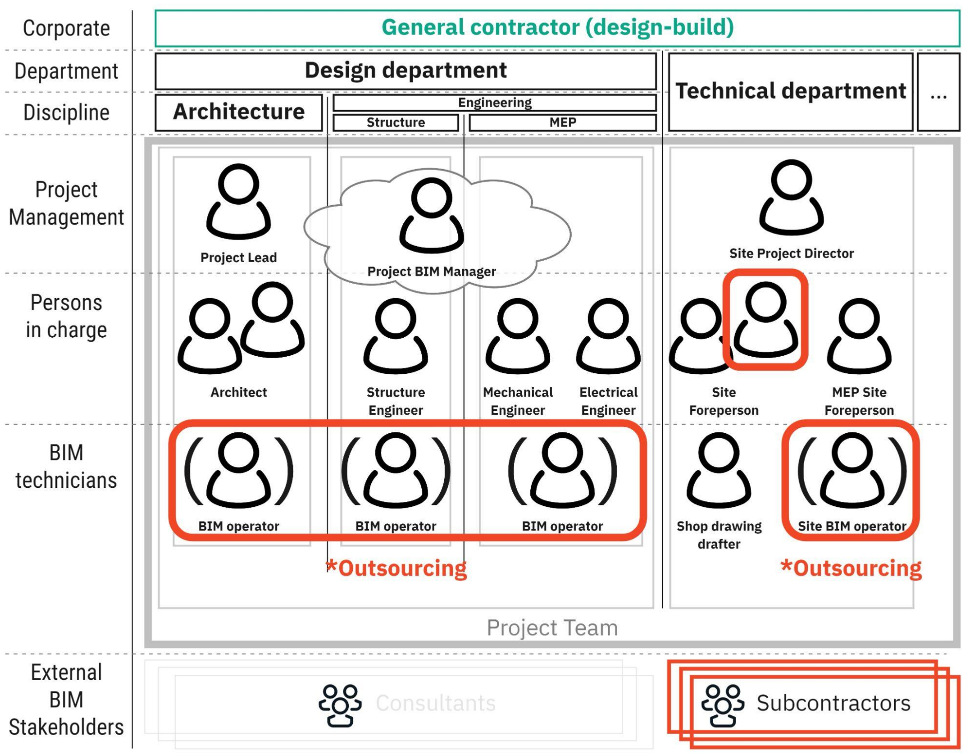

Figure 7. Project collaboration in design-build general contractor, by author.

Summary

BIM has become an indispensable tool for today's building projects, with little doubt remaining concerning its significance in the design and construction process.

This chapter first explored the diverse definitions and plausible origin of the concept. The advantage of BIM is characterized by some key phrases such as consistency among presentations, clear and comprehensive communication, front-loaded decision making, connections to digital technologies, and utilization of attribution information inside.

The AEC industry faces an extremely difficult situation to address today's social problems. The building demand will sustain or even increase against the backdrop of urbanization. Enhancing productivity is an urgent matter due to the declining working population. Advanced design and construction methods are indispensable to fulfill the increasing requirements of green buildings. BIM is regarded as one of the promising solutions for these challenges.

Despite its clear necessity, implementing BIM itself contains numerous problems. Due to the nature of the AEC industry, digitization of the current work process encounters many missing pieces. The government should play a vital role in spreading BIM to the industry, yet the Japanese ministry is reluctant to respond quickly. The commonly adopted contract scheme, design-and-build, does not automatically fit into the international workflow. Finally, the steep learning curve led to the need for BIM specialists. It can result in hollowing out the practical skill of the influential BIM organizations.

Chapter 2: Introduction

Problem Statement and Expected Contribution

The need for BIM is evident. It has become a central information source to connect to emerging digital technologies. Promoting BIM further is an indispensable piece to mitigating the problems of the AEC industry.

While the concept of BIM and AEC industry problems are universal, the direct introduction of BIM workflow into Japanese building and construction projects poses substantial unsolvable problems. The issue does not seem to lie in the awareness; it would rather be in the misinterpretation of the BIM workflow to the locality of the Japanese AEC industry. Besides numbers of past studies to analyze the status of BIM at the level of project, organization, and nation, it is vital to have the human-centric analysis approach to decipher the situation directly applicable to Japan's cases.

The practitioners are suffering from the lack of a talented workforce. Granted the low fluidity in Japanese jobs persists, the simpler tasks, such as model creation and coordination, can be supported by the outsourced BIM personnel, so-called BIM operators. Still, the managerial function needs to be undertaken by the existing experienced personnel.

Standardization is the most solid approach to minimize workflow redundancy and bridge communication regardless of the BIM literacy. The government does not initiate the discussion for this area as examined in the later chapter, the bottom-up strategy by the private sector is the only feasible approach to spread the workable standard. Some housing-focused general contractors are eager to develop their internal BIM regulations since the project workflow has been solidified for the deliverables. However, non-residential ones are fated to undertake any type of building, including commercial, educational, healthcare, or religious—accordingly, the scale and timeline exhibit tremendous variety from project to project. Substantial numbers of their project are not design-and-build; they may be design-bid-build or require the joint venture with other firms. The workflow is completely unpredictable until the project order is placed: therefore, a flexible means to explicate the activities inside project BIM is a plausible technique to resolve the challenge. As their influence on the whole Japanese AEC industry is immense, the methodology to navigate them for the successful BIM project is not solely for those enterprises but also the rest of the ecosystem.

Technically, BIM software is a conglomerate of existing applications such as modeling, viewing, rendering, engineering, coordinating, and data management. Obtaining fluent BIM software skills naturally requires significantly more time. Eventually, many practitioners find it nearly impossible to master alongside the ongoing project tasks.

Apart from that, externally monitoring activities occurring inside the model is not easy. Visual monitoring the progress in 3D view certainly provides progress in model making. However, the detail development or documentation process requires another view to monitoring. Moreover, some input, for instance, entering a unit price information to a balustrade, is an invisible contribution to the project unless explicitly inquired. As the multimodal operation is available in one environment, the activities are overwhelming without simplification. Overall, an attempt to estimate the BIM activity only by watching a 3D model is similar to observing the construction work outside of hoarding. It may provide a sense of progress but stays far away from the assessment and analysis.

Therefore, a system that explains the activity inside a BIM project can be identified as the core to communicate BIM adoption, implementation, and utilization. Accordingly, the method should depict the characteristics of practitioners involved in the project BIM environment. The landscape expected will attribute the mean accomplishment to those who made and spot on some who implicitly contribute to the project. The two main problems this dissertation tackles are deciphering such signals from the activity and interpreting them into the local context.

Research Question

For BIM to be welcomed as a common language among the Japanese stakeholders, we need an analytical method that provides a taxonomy of BIM activity for laypersons to comprehend the events occurring inside the model. We expect the methodology to identify the key persons in the collaborative projects. Portraying the cooperative BIM personnel enhances the likelihood for BIM to be effectively used throughout the project.

The research question of the thesis is threefold as follows:

RQ1: Can we decode the cross-functional BIM activity from data?

- A versatile method that flexibly fits project conditions is especially needed to analyze the design-and-build projects in Japan.
- Data should drive the analysis to precisely reflect the behavior across the disciplinary, regardless of modeling-related or not (geometrical or attributional)
- The result should be visually comprehensive to address all project stakeholders inclusively, such as non-BIM professionals or project clients.

RQ2: How can we represent the traits of BIM collaboration in projects?

- Because of the nature of general contractors' scope of work and the dynamism of the building projects, multiple comparisons should be empirically made at different levels such as:
    - Organization level
    - Project level
    - User level
    - Command level

RQ3: How can we identify the "keystones" in organizations?

- The analysis may reveal that the designated specialists undertake most BIM-related tasks.
- Nevertheless, there should exist some practitioner who acts as a collaboration hub.
- Deciphering the activity to identify such professionals will depict the shape of successful collaboration under the Japanese AEC ecosystem.

Author's Epistemological and Ontological Positions

As the first-class licensed architect-engineer (Ikkyu Kenchikushi) since 2011, the author has more than 15 years of experience in AEC since joining Takenaka Corporation in 2006. His design works for commercial projects include Forever XXI, Shiseido Headquarters, and Kanda Holdings (all in Tokyo). His engagement with residential projects includes multiple high-rise buildings in the Tokyo metropolitan area.

The author was first involved in an international BIM project as a BIM manager in 2012. Since then, with over nine-year BIM practice and management experience, his BIM management projects include CapitaGreen in Singapore, Changi Airport Terminal 4, and the new head office for Japan Broadcasting Corporation (NHK). His computational design projects include Tokyo Disneyland, Nagoya Castle Reconstruction, and multiple stadium projects in Japan. In addition to the four-year experience for the international projects from 2012 to 2016, the author has more experience in the international BIM collaboration, including Bosch Yokohama head office.

From the past BIM project experiences, the author recognizes that BIM use, in reality, is far from ideal. In numerous design firms and contractors, most in-house practitioners hesitate or even dislike to access the model despite their awareness. While most companies grant hours of BIM training programs to the employees, project models are created and maintained by very limited exclusive BIM specialists. The decision-making, design approval or many other pivotal project events only happen on 2D drawings in PDF or even on paper.

As a BIM-enabled project architect, the author in person deeply appreciates the benefits of the BIM environment. Numbers of time-consuming tasks are drastically facilitated. For example, one-time design rectification is reflected in all relevant drawings, eliminating the inconsistency of the drawing. Area calculation can be completely automated after the first tabulation is done. Color filters are applied onto drawings with a minimum operation to apply the configuration to the drawing set. Even though these low-hanging fruits are available by an average BIM skill, these full benefits will not be enjoyed when BIM tasks are merely outsourced.

Structure of Thesis

The chapters after this introduction are organized as follows (Figure 8):

Chapter 3 identifies relevant research topics and reviews the existing literature.

Chapter 4, as the preparatory study, examines the readiness of BIM in Japan. It is examined from several aspects; the coverage and richness of industry-wide BIM guidelines, the synthesis of preceding fact-finding surveys, and the summaries from professional's open discussions.

Chapter 5 identifies the conceptual framework based on key existing literature.

Chapter 6 explains and justifies the method applied to the following chapters.

Chapter 7, as the first empirical study, presents the application of visual analytics to the collected BIM activity records. The data was collected through the BIM learning workshop to normalize the skill level and input project data for cross-comparison of participants.

Chapter 8, following the earlier chapter, presents the result of visual BIM log mining applied to the dataset collected from a broad range of organizations. The chapter proves that the proposed method deciphers the BIM activities fulfilling the monitoring needs of non-BIM practitioners and managers.

Chapter 9, as the last empirical study, applies the method to another dataset collected from one of the largest Japanese general contractors and its subsidiary company. The analysis, including supplemental big data, focuses on the workforce proportion of permanent and temporary staff. The interview conducted on selected permanent staff follows the analysis result to investigate the factors for key practitioners in successful BIM cooperation.

Chapter 10 federates the findings from the earlier chapters together with the background and discusses the discoveries throughout the thesis. Limitations of the research and recommendations are also presented.

Chapter 11 summarizes the proposed method, significance of findings, and contribution of the study to answer the research questions.

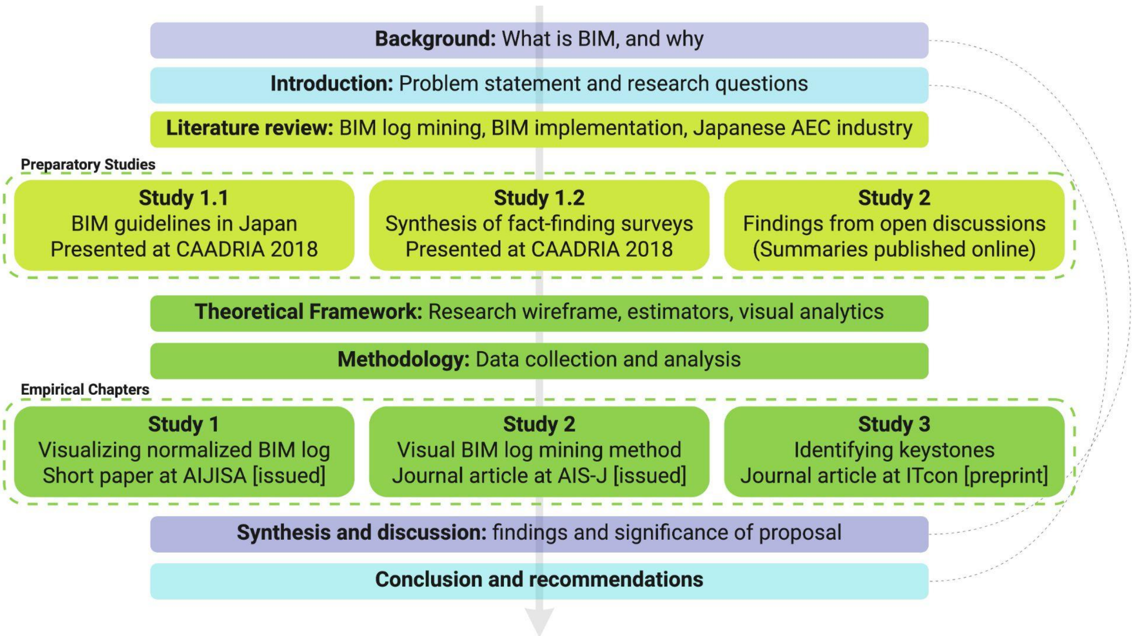

Figure 8. Structure of the thesis.

Chapter 3: Literature Review

Overview

This chapter defines four relevant discussion areas for this dissertation in surveying existing research. At the core of this thesis, the analytical approach is termed BIM log mining; multiple researchers have published papers on the subject in recent years. The topic is not BIM alone but rather a concept applying process mining to the BIM field. The relationship between the two and principal articles will be introduced.

The literature on BIM is extensive and forms many subcategories. The most relevant to this particular study is the publications on BIM implementation. Each organization faces challenges in adopting BIM. This paper investigates the types of challenges, the methods to overcome them, and the metrics to measure the success of BIM implementation.

It is worth considering the peculiarities of Japan's AEC industry compared to other nations. The key research papers will examine the process by which Japan's unique architectural culture has been westernized to the present day and the characteristics of Japanese general contractors who hold particular influence on Japan's industry today.

Furthermore, professional skills and human resources will be explored: BIM is often considered a professional skill in its field, just as CAD has been in the past. From that point of view, BIM appears to be a task that requires specialized personnel, and such professionals certainly exist. However, differences likely lie in the ideal vision of BIM personnel sought from the Western perspective, which presupposes a division of labor, and from the collaborative structure of the workforce in Japan. Articles related to the prerequisites necessary for this discussion will be studied. Finally, we synthesize the findings from existing literature surveys and discuss the gaps contained therein. The topics with the representative authors and their relationships are outlined in Figure 9.

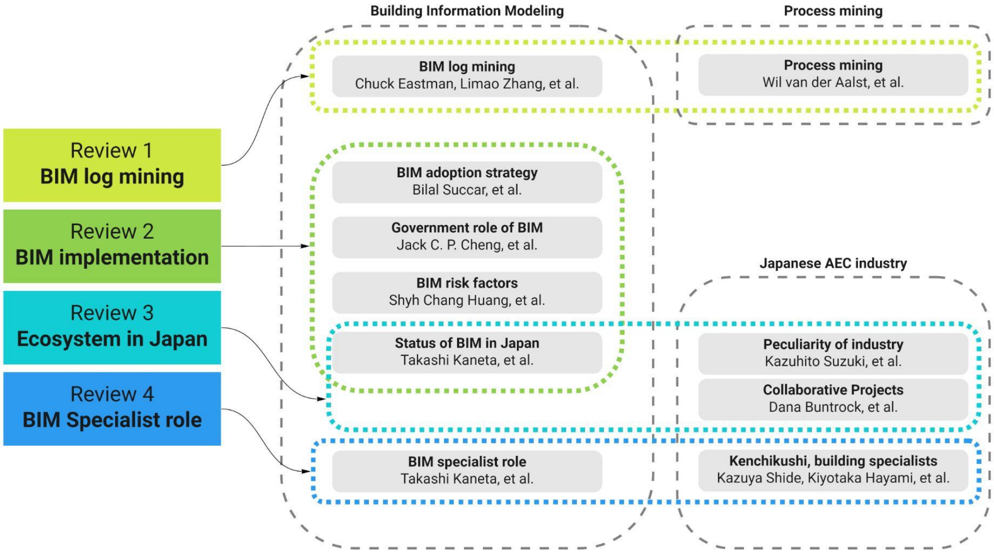

Figure 9. Overview of literature review, the relationships of categories.

BIM Log Mining

While BIM maximizes its benefits when the designers use it, this may not be feasible in some cases. It is highly feasible when the project size is modest or the design period is sufficient. Conversely, large-scale or short-term projects inevitably require collaboration.

The BIM human resources employed are often external in Japanese general contractors. The project BIM Manager is often from the architecture design department, although having a full-time dedicated professional is not rare. In general, BIM technicians are underpaid compared to architects, but there appear to be reverse cases [96]. Project-specific BIM team structures have not been fully studied.

Recent research has found that BIM log mining is practical for investigating productivity in BIM. BIM log mining applies an analytical approach to command history automatically recorded by BIM software to discover implicit patterns in use without requiring extra effort from BIM users. BIM log mining is expected to increase BIM performance and enhance model communication. This study seeks to further contribute to the potential of BIM log mining by proposing a novel approach to mine the BIM logs.

Log mining, or log analysis in the broader context, is a technique that leverages data mining to analyze logs, which are records related to the activities occurring on a system. We expect log mining to gain situational awareness, discover new threats, and extract actionable findings automatically. Though the technique can be applied across industries, it is particularly known in specific fields, for instance, web-based systems known as web log mining [97]–[99]. The common purposes of log mining are anomaly detection [100] or result optimization [101]. Some studies have suggested increased productivity from log mining. For example, in the automotive industry, Niimi et al. succeeded in extracting the tacit operational skill of 3D CAD modelers in vehicle design by analyzing operation logs [102].

Autodesk Revit, one of the most common integrated environments worldwide, automatically generates detailed session records called journals for troubleshooting purposes [103]. In recent years, several studies have emerged that applied the technique to the design log of BIM software. The first application was reported by Yarmohhamadi et al. as the pattern mining methodology to extract sequences commonly shared among users [104]. This study proved that the unstructured BIM log files from Autodesk Revit could transform into Generalized Suffix Trees (GST) data structures through appropriate data treatment and that meaningful information can be derived by analyzing the dataset. The subsequent research further investigated implicit patterns in log files and empirically characterized the performance modelers [105]. Zhang et al. proposed a pattern retrieval algorithm to discover typical design command sequences [106]. Those reports mainly addressed the command names issued during the operational sessions. The primary intention of these pieces of research was to establish the monitoring process of modelers' performance for achieving higher design productivity and effective management. However, as briefly stated by Zhang, the measurement of design productivity is much more difficult than that of construction productivity. Thus, he emphasized that the proposed metric should be interpreted in the context of other performance measures for the project instead of replacing or undermining other performance metrics to assess design projects [106]. Pan et al. classified designers into three clusters using a clustering method called node2vec-GMM, explaining that the three clusters have different characteristics and understanding them can provide data-driven support for organizational management. This study has already explicated the utility of clustering for BIM event logs. In particular, from the perspective of productivity, methods for contextual prediction of design work productivity [107] and methods for exploring typologies of design work have been proposed [109]. Forcael et al. have published an attempt to measure the contributions of cross-disciplinary BIM users from BIM logs [110].

These BIM log mining methods are strongly inspired by past research that has been treated in business process management. The significant past contributions include Aalst's publication, which holistically presents various process mining techniques that aid organizations in uncovering their business processes [111]. Sequence mining is another domain that addresses the pattern discovery problem. Past contributions include the paper by Wang et al., which presents an efficient algorithm to mine frequent closed sequences without candidate maintenance [112]. The visualization of event sequence data influences the application of visual analytics. The essential existing research includes the paper by Du et al., which describes 15 temporal event sequence analytics strategies grouped mainly as extraction strategies, temporal folding, pattern simplification strategies, and iterative strategies [113].

One of the known challenges to BIM log mining is how the prerequisite productivity can be related to BIM activities -- the more active users are in BIM, the more they contribute; yet the reverse is not necessarily true. Another problem is the dependence of analysis environments on applications. Since the mining process relies on the log files produced by applications, it is difficult to study to the same extent with software that does not record log files. One possible strategy is to mine common data formats such as IFC [114]. Also, Gao et al. has made a significant contribution to draw parallels to the BIM log mining technology in generic 3D modeling software named Rhinoceros[108], [115]. However, such information, including editing processes, undone tasks, and settings necessary for collaboration, cannot be retrieved from model files alone.

Blockchain can potentially solve these problems [116]–[118]. Theoretically, any BIM contribution could be analyzed if all actions are recorded using the Blockchain as a ledger. However, there are still numerous challenges associated with implementation, particularly because of the amount of data involved.

BIM log mining was first intended for design productivity by focusing on frequently-issued modeling commands. Its target use gradually expanded to cover other factors, such as team collaboration or modeling strategies. A BIM team communicates with more stakeholders as the project progresses. The BIM tasks on such project stages are widely varied and include non-modeling-related activities. Therefore, BIM log mining that flexibly analyzes cross-functional BIM activities based on the current requirement is a novel approach that contributes to the body of knowledge and provides a valuable tool for improved BIM project management.

BIM Implementation

Chien et al. identified thirteen risk factors in BIM implementation related to the technical, management, personnel, financial, and legal aspects of the implementation, with the management of BIM being a primary risk factor in BIM adoption. Among these factors, four factors are related to the transition of management and workflow: F3 (challenges in model management), F5 (challenges in management process changes), F6 (inadequate upper management commitment), and F7 (challenges in workflow transition) [94]. In particular, management's strong commitment is indispensable in avoiding or reducing the associated risks in BIM projects.

Alternatively, Fazli et al. described that project managers generally have minimal knowledge of BIM and are usually unappreciative of the benefits of BIM, especially in construction projects. Furthermore, BIM is still perceived as a newly required skill in the industry, and learning BIM demands a steep learning curve [119], [120]. BIM projects are often overseen by managers who have only limited knowledge of BIM or adhere to the conventional drawing-oriented workflow. Attempts to change this situation all at once may prolong these problems even further.

Efforts have been made to mitigate such a mismatch. Several studies have proposed performance monitoring systems to determine the actual BIM activities undertaken in a project. The systems measure and visualize how BIM specialists behave, which facilitates BIM managers in improving BIM productivity and in defining an appropriate staffing strategy. Such monitoring systems may potentially become a self-diagnostic system for the project. Bryde states that BIM can be a catalyst for project managers to reengineer their process to integrate better the different stakeholders involved in modern construction projects [121].

BIM projects are often large and complex, where internal collaboration can significantly influence overall productivity. Zhang et al. applied the social network model to analyze BIM designers' characteristics and social performance in an architectural firm. The research shed light on the management issues to proffer the system for the appropriate staffing strategy, the assignment of the right design tasks, and the discovery of bottlenecks in the design process development [122].

Past research has made a substantial contribution to BIM management. Tauriainen et al. analyzed design management issues and identified the major causes of the problems, including the insufficient BIM knowledge and experience of BIM managers [123]. Barison et al. outlined the areas of responsibility of multiple BIM specialists [124]. Uhm et al. categorized BIM roles into eight categories by analyzing job postings and analyzing the relationships between them [125]. Kassem et al. identified the core competencies of four key BIM specialist roles, including the BIM Manager and the Information Manager, revealing substantial overlap across all roles [126]. The study regarding BIM team and talent management increases its necessity. The 2013 McGraw Hill SmartMarket Report stated that most contractors encourage BIM expertise in team formation [127]. Considering the increasing demand, it is evident that today, BIM ability has a greater influence over the startup of a project team. Davies et al. identified important soft skills, such as communication, conflict management, negotiation, teamwork, and leadership, for BIM project teams generally overlooked [128]. Davies et al. imply that such skill developments are necessary to move forward from the implementation stage to the leveraging stage.

The effort has been made to develop measurement methods for the model use and level of implementation [129]–[132]. Wu et al. exhaustively overviewed nine mainstream BIM measurement tools and discovered that those tools have a unique emphasis on understanding users [133]. Most BIM measurement tools have organization or human-related measurement features. These methods mainly evaluate the use of BIM-related tools, the availability of key personnel, the provision of education programs, or stakeholders' satisfaction.

The literature mentioned above supports the conclusion that the magnitude of each aspect of BIM, such as experience, cost, workflow, or contracts, is almost equal.

Ecosystem in Japan

Up until the early modern period, the construction industry in Japan was represented by a profession called *toryo*. The five skills were identified as crucial for any *toryo* in the secret book of teachings "Shoumei" passed on in the family of Masanobu Heinouchi, a *toryo* for the Tokugawa shogunate, namely; drawing lines, calculation, manual work, painterly work and sculptural decoration [134]. The integrated design and build system is Japan's autogenous procurement method for the construction industry. The origins of this system can be traced back to the early Edo period when a few buildings under direct management were undertaken as contractual job [135].

The Western architect concept was introduced during the modernization process. The profession of design architect was born as the Imperial College of Engineering was established in 1871. This movement did not lead to the separation of design and construction as is common in the West; instead, convergence with the integrated design and construction method of *toryo* was sought. Kingo Tatsuno, one of the earliest architects in Japan, is regarded as its advocate [136].

Five major companies were thus born, including Shimizu, Kajima, and Takenaka Corporation, whose origins can be attributed to traditional carpenters and Obayashi and Taisei, established after the Meiji era. The five general contractors account for over 10% of the total industry share. All these corporations are equally competitive, and all possess maintenance, management, and research capabilities in addition to design and construction. Although this formation is unique worldwide, it has not been a major subject of international research.

Against the backdrop of increased construction investment driven by post-war reconstruction, Japan's major general contractors expanded overseas in the 1970s, particularly Southeast Asian countries, Eastern Europe, and Africa. In the 1980s, the economic boom known as the "bubble economy" boosted capital investment in construction and increased research and development expenditures in technologies, including robotics [137], [138]. Multiple studies have been conducted to analyze their business schemes [139], [140] as they were an emerging competitor in the international market. The research focused out as the bubble economy had burst and other economies, such as China, had equalized. Nowadays, domestic researchers have mainly conducted several studies to increase the competitiveness of domestic industries [141], [142].

From its origin, the Japanese architectural production process is extremely collaborative. The designer and the builder stand on an equal footing; the craftsperson who carries out the work on the site talks directly with the designer, and the designer incorporates their opinions. While this cooperative relationship is commonly encountered in Japan, the Western concept of the architect finds it somewhat surprising. On the other hand, this flexibility has formed a business practice where little attention is paid to written contracts. Work may begin with a verbal agreement to realize the architect's wishes [85], [143]. The contractual correlations that govern the production system of the Japanese architecture project are dominated by relational contact [135].

Integrated Project Delivery (IPD) is a project scheme often discussed in parallel with the BIM implementation [144], [145]. IPD is known to be conceptualized by referring to the Toyota Production System. The ultimate aim of IPD is to constitute the ecosystem that supports the benefit for the project owner. Although the pre-modern Japanese AEC industry system possessed such a concept, the IPD approach is now being newly explored after grafting the Western construction culture. Interestingly, some attempts to define a new Japanese version of IPD are reinterpreted through international trends.

In the past, Japanese general contractors had a gentle division of functions, and the professionals were not bound by the scope of work but took charge of the entire project and responsibility for improvement. The greatest advantage of design-build is the smooth transition between project phases and the shortened overall project period, which cannot be achieved by design-bid-build. In addition, the collaborative dialogue in an environment with few conflicts of interest has helped the industry be recognized for the high quality of its deliverables. Therefore, Japanese building specialists generally expect BIM to enrich the toolset to conduct broader expertise rather than enhance the quality of buildings or shorten the construction period. It suggests, however, that the positive motivation for introducing BIM may not arise without the clear problem recognition towards the current workflow.

BIM Specialist Role

Despite the presumption that designers themselves will create the models, BIM may require specialists to take on this role, depending on the situation. Apart from BIM-skilled designers, global needs exist for BIM-focused experts. In such cases, modelers who undertake relatively simple tasks like modeling under the instruction of the supervisors may be more suitable, assuming the existing job responsibilities of the architect. Coordinators are needed in large-scale projects to identify problems that arise when multiple models, such as structural and MEP models, are integrated. BIM managers and directors can oversee these coordinators and be responsible for project BIM [126]. Although these names and roles are not internationally consistent, multiple studies have typified them from investigations in the human resources market [146]–[149].

It is typical for Japanese architecture projects to collaborate with a drafting specialist called a CAD operator. It is especially prevalent in major architect firms or general contractors, who have a massive influence on the industry’s trend. This system lets designers and builders concentrate more on project management by outsourcing the drawing works to CAD operators.

CAD operators specialize in drafting, detailing, and sometimes even data management. It incentivized CAD operators to fit into individual corporates’ drawing conventions. Collaborating with skilled CAD operators is essential for the betterment of projects. Hence it is desired to have such BIM operators for successful BIM implementation in Japan.

Since the days of 2D CAD, the software operation has been often regarded as an exclusively professional task, and there have been people dedicated to this service termed as CAD operators

[95]. Many CAD operators merely input drawings created by other designers into the computer [150]. While CAD skills are considered indispensable for any architect today, collaboration with operators is common, particularly in large-scale projects [151]. The rationale for this, especially in Japan, is the two-tiered structure of architects or building specialists, namely the permanent employees directly hired by the giant organizations and external personnel, who are dispatched staff generally considered to be in charge of auxiliary tasks. Kaneko explained that builders are predisposed to consider BIM as a matter of necessity or imposed by external factors. He also pointed out that it depends on the external operator at the early implementation stage. Thus skills and know-how do not accumulate inside the company [152].

Experienced CAD operators may possess extensive know-how for the proprietary drawing conventions of major industrial players, and that proficiency incentivized them in obtaining job opportunities. In the extreme, CAD operators often accumulate more profound insights on the drawing protocols than the contractors' in-house professionals. Some enthusiastic CAD operators may be motivated to upscale their skills to become BIM operators; however, most experienced yet aged CAD operators are not willing to alter the workstyle into a new one. The main contractor seeks such versatility to the operators for immediate resolution of daily problems.

This phenomenon is fairly unique internationally or different from other BIM-advanced nations. It is partially explained by the uniqueness of the architect license called *Kenchikushi*, which covers architectural design, engineering, authority submission and construction supervision. Before establishing the architect's license in 1950, the Western concept of the architect had emerged by the end of the 19th century in Japan, as previously mentioned. Nonetheless, the design profession coexisted without integration as part of the caliber of conventional toryo and the Western architect structure. Despite repeated deliberations, the law establishing the architect system failed to materialize for more than half a century [153], [154]. In the meantime, there were agents called "architectural agents" during this period, who were undertaking the work of applications to the relevant agencies, including drafting works [155]. Specialists handling the peripheral work of the architects have long existed in the market and assisted their core business.

BIM personnel are also often assigned as operators from this context, yet very little literature has been written about the statistical facts and their responsibilities. As a fragmentary fact, it is reported that dispatched personnel, such as shop drawing drafting or CAD operator, constitute an occupation that female junior college graduates are likely to continue with while exercising their expertise. Regular employees' more flexible working style facilitates female professionals to continue exhibiting their expertise even after child-raising [156]. In the Japanese construction industry, where the job liquidity is particularly low, the average length of service for new graduates of companies exhibits extremely long periods. By contrast, external personnel are hired on a short-term basis and are generally treated inferiorly to employees. This relationship may benefit the specialization of external personnel and the rationalization of labor costs in projects. However, it remains a concern that it could hollow out the main players' primary knowledge and skills in BIM.

Concerns persist even if we affirm the collaboration that has taken place so far. As defined at the beginning of this thesis, the building is a fruit of collaboration. Dependency on external specialists will lead to the hollowing of internal knowledge, where the BIM-related tasks will be isolated. Under such circumstances, revitalization of communication is unlikely to be achieved. In other words, sole outsourcing to external parties may be counterproductive to the effects initially expected from BIM. All parties involved must have dialogue and make decisions on the same source of information. Therefore, if we keep accepting the status quo, it will be severely difficult to accomplish the major goal of improving communication in BIM. It is imperative to conceptualize and implement work assignments that contribute to the big picture.

Synthesis and Gaps Exist in the Literature

First, BIM log mining has proven to be an emerging field. Past research has demonstrated its usefulness. However, more diverse analysis methods must be devised to resolve real-world industrial issues. Especially, more datasets should be experimented with. Research has already reached the stage of assisting the designer's thinking by interpreting the semantic linkages in the logs.

Nevertheless, existing research assumes productivity within a single area of expertise based on labor division. In stages such as the late design and the construction stages, where collaboration between multiple disciplines occurs, it is only possible to compare the talents within a single discipline. Still, it is impossible to evaluate cross-disciplinary comparisons for the entire project team. This is a shortcoming in analyzing collaborative and cross-disciplinary project teams in Japan.

Second, many research methodologies exist that encourage the adoption and implementation through success metrics like maturity measurement. It conversely implies that a single metric cannot thoroughly measure BIM utilization in projects and organizations. Projects are more diverse than organizations. For example, in a joint venture, the same duties are divided among two or more companies. In many cases, highly specialized production equipment and security equipment are designed by expert consultants. It is not rare to see projects where the contractual schema diverges over time. It should be rational to devise a method to satisfy individual needs through a dynamic analysis method, rather than separating tool-sets for different circumstances.

Third, although the forms of contracting and collaboration in the Japanese building and construction industry are unique worldwide, not much literature has attempted to connect this uniqueness with international business practices. Compared to those analyzing the Japanese construction industry in light of its expansion into overseas markets, there has been very little discussion of introducing foreign methods into the domestic industry since the Meiji era. It indicates that a substantial amount of interpretation is still required to supplement the perspectives when connecting methods like BIM to domestic methodologies.

Finally, BIM specialists generally appear to be in short supply, and Japan is not exceptional. BIM personnel in Japan have inherited from their historical background the context of outsourcing the work of designers who are placed in a position of responsibility throughout the design and construction process. Surprisingly, little research has been done on BIM operators, formerly CAD operators, who undertake those BIM orders. While many operators are present, little information about their working methods and fundamental statistics are available. As a result, discussions on collaboration premised on the operators' existence have been left undiscussed, and so have strategies to augment operators to resolve the human resource shortage.

Summary

In this chapter, the subject points of previous research have been examined through the literature review. The interpretation that reflects the local ecosystem is essential for the Japanese AEC industry to leverage BIM as an internationally accepted platform. Concerning BIM human resources in particular, although collaboration with operators should be a prerequisite for large-scale projects, there is little research on BIM specialists in Japan. BIM log mining is a plausible approach for investigating the actual state of collaboration with operators. As this area is novel, building datasets and methods will significantly contribute to knowledge. Given the diversity of projects and the fluidity over time, it will be extremely valuable to devise dynamic and flexible analysis methods.

Chapter 4: Preparatory Studies

Overview

This chapter discusses several areas for which the existing literature review alone does not provide sufficient information before the main study. The findings are based on the research and open discussions conducted by the authors.

BIM use has been spreading in Japanese private projects over the past years. It becomes more actively discussed as paramount to rationalize the industry by leveraging BIM technology. Nevertheless, the Government also has a high expectation of BIM to enhance the industry's performance. There seem to be missing pieces in the industry to expedite the use in Japan. This research tries to identify the factor that hinders the smooth BIM implementation.

Another problem concerns the identification of problems by practitioners. We attempted to collect the opinions of industrial and educational professionals through the symposiums to bring the issues recognized by the author's epistemology closer to the challenges of the entire industry.

Preparatory Study 1: Industry-wide Readiness for BIM

In this section, we examine the status of BIM implementation from multiple sources of information publicly available. Firstly, the research analyzes the shared BIM knowledge in Japan. There are multiple types of information useful to the practitioners, such as BIM standards or BIM guidelines. The authors compare the availability and content coverage with those from other countries to examine its characteristics. Secondly, the authors study statistics to see the situation from the practitioner's side. The research attempts to find the crossover of benefits and problems of BIM from different surveys. Finally, the conclusion will be made upon the discussion based on these two points of view.

BIM guidelines in Japan

Kassem et al. defined it as Noteworthy BIM publications (NBP), which are publicly-available documents developed by various academic, governmental and industry entities aimed at a broad audience. They intended to promote BIM understanding, regulate BIM implementation or mandate BIM requirements [157]. Since the authors aim to examine the industry-wide common language for BIM, this paper aims to examine "BIM Protocol," which includes BIM standards and guidelines.

The most holistic and thorough research for this field was made by Cheng et al. [79]. However, the protocols in Japan were not extensively covered, likely due to the unavailability of well-translated information. This section attempts to overcome such a drawback and add the implication to the analyzed situation.

MLIT BIM guideline

MLIT issued the BIM guideline in March 2014, the only national BIM Protocol before 2017. This MLIT BIM guideline is applied to the public projects when BIM is implemented by the own decision of the contractor (architect or builder) or when proposal-based technical studies are needed. BIM has not been compulsory; it has not been mandated to projects except for a few pilot projects. MLIT BIM guideline focuses on basic concepts and examples of technical studies expected from BIM use. Further information for data standardization is left on the contractor side.

The MLIT BIM guideline consists of three sections; (1) General Rules – 6 pages, (2) Design Process – 16 pages and (3) Construction – 3 pages. The explanation part of the document repeatedly remarks that the model can be developed depending on the project's need, and it is possible to further the model detail at the contractor's decision. It can be said that there is significant room for architects, engineers, and builders to customize the configuration per their preference. However, on the other hand, this guideline does not orient to regularizing the contents and their data system to facilitate data interoperability over projects.

The comparison with other BIM Protocols is made to understand the characteristics of the MLIT BIM guideline. Table 1 shows the contents of BIM Protocols from the UK, Hong Kong, Australia, Singapore, the US, and Japan. Cells are colored when the BIM Protocol has the relevant contents in it. The number of "+" in the table shows the concreteness and richness of detailed information for each regulation to overview both coverage and depth of each BIM Protocol.

Compared with other Protocols, MLIT BIM guideline does not state Project BIM Execution Plan (BEP), collaborative BIM working, folder structure, naming conventions, and presentation styles.

BEP is vital in BIM projects to strategize the extent of BIM implementation in specific projects. Thus most BIM Protocols elaborate on creating and agreeing on Project BEP. MLIT BIM guideline states that the execution method (including the name and version of BIM software and simulation software), execution contents and organization shall be mentioned in Project Execution Plan, which Design Work Common Specification regulates. Therefore BEP needs to be associated with the existing PEP protocol. However, detailed information or template is not provided within the document.

Although presentation style, which regularizes the appearance in drawings or other outputs from models, is not straightforwardly mentioned in MLIT BIM guidelines, it is related to the definition of LODs. MLIT BIM guideline appendices tables show the model LODs in basic design, detail design, and construction phases. An annotation with each table states that the detail level of geometric information shall refer to Design Drawing Standard for Architectural Construction, scale 1/100 et cetera. The guideline standardizes the model contents from the 2D presentation, for which the national standard already exists. After that, the model is regulated to have enough detail to represent it.

The room name convention at the design phase refers to other MLIT outlines issued in 2006 and 2007, and the material and apparatus naming is based on MLIT standard specification. The rest naming is not regularized in the guideline.

Table 1. Coverage and content richness of nationwide BIM standards in selected countries.

Topic	Coverage							
Abbreviation	**UK AEC**	**HK CIC**	**AUS NAT**	**SG BIM**	**SG Guide**	**Penn US**	**NBIMS US**	**MLIT JP**
Title of BIM standard	AEC BIM Protocol (The United Kingdom)	CIC BIM Standards (Hong Kong)	NATSPEC National BIM Guide (Australia)	Singapore BIM Guide	Singapore BIM Essential Guide	Penn State BIM Project Execution Planning Guide (US)	NBIMS (US)	MLIT BIM Guideline (Japan)
Version	2.0	DRAFT	1.0	2.0	1.0	2.1	2.0	1.0
Year of issue	2012	2015	2011	2013	2013	2005	2012	2014
Definition								
Terminology / Definition	++	+++		+++		+++	+++	+
BIM Uses		+++			+++	+++		
LOD								
LOD Definitions		+++	++	-				+
LOD Responsibilities		+++						
LOD Specification		+++						+
Best Practice								
Best Practice	++					++		
Project BIM Execution Plan								
Model Deliverables			+++	++	+++	+++		
Organization Start Ups					+++			
BIM Vision / Area of Interest					+++		++	
BIM Goals					+++			
BIM Standards					+++	++		
Procurement Strategy			++	+++				
Data Reuse			++					
BIM Roles and Responsibilities	++	++	+++	++	+++	++	+	
Team Competency and Training		+			+++			
Client Requirement		++			+++	+++	++	
Design BIM Management Plan			+++					
Construction BIM Management Plan			+++					
Project BIM Execution Plan	+	++		++	+++	+++	+++	
Project BIM Meetings	++		++			+++	+++	
BIM Overview Mapping						+++		
Capability Maturity Model (CMM)							+++	
Collaborative BIM Working								
Common Data Environment	+	+		++		++	+++	
Model Submission (for Approval)	+	+						
Data Security (Back-ups)	+	+		+				
Model Review	+							
Interoperability								
Incoming Data Management	++							
Intended Use of Model	++					++		
Data Transfer across Platforms	++			++			+++	+
Open Standards			+++			++		
Data Segregation								
General Principles	+++	+						
Division	+++	+		++				
Referencing	+++	+					+	
Revision Management				+	++		+	
Interdisciplinary References		+++					++	+
Modeling Methodology								
Model Development Methodology	+++	+					+	+
Graded Component Creation	+++						++	
Drawing Compilation	++	++		++				
Spatial Location and Coordination	+	++	+++	++	+++			+
Units and Measurement	+++	+						
Space / Volume Measurement			+++					-
Model Archiving		+						
Model Quality Assurance		+		++	+++	++	++	
Existing / Site modeling Guidelines			++		+++			
Conceptual Mass Model Guidelines					+++			

Topic	Coverage							
Abbreviation	**UK AEC**	**HK CIC**	**AUS NAT**	**SG BIM**	**SG Guide**	**Penn US**	**NBIMS US**	**MLIT JP**
Archi Model Guidelines		+	++	+++	+++			+
Structure Model Guidelines		+	+	+++	+++			+
MEP Model Guidelines		+	++	+++	+++		++	+
Construction Model Guidelines			+++		+++			+
Digital Fabrication			+		+++			
Construction Planning			++		+++			
Other Simulation and Analysis							+++	+
4D Simulation			++		+++			
5D Cost Estimation / Quantity Takeoff					+++		+++	-
FM / As-built Model			+		++	+++	+	+
COBie / commissioning			++			+++	+++	
COBie Information Delivery							+++	
Handover Strategy							+++	
Collaboration								
Model Federation		+		+++			+	+
Clash Coordination		++	++	+++				+
Model Sharing over Phases			++	+++	+++		+	
BIM Coordination Meetings			+++				+	
Model Structure / Subcontractors			+					
Folder Structure and Naming Conventions								
Project Folder Structure	+++	++	++					
General Naming Conventions	+++		-					
Model File Naming	+++	++	-		+++			
Division Naming	+		-					
Library Object Naming			-					
Object Property Naming	+		-					
Space Naming and Coding			++					
Equipment Coding			++					
View Naming	++	+	-					
View List Scheduling	+		-					
Data Organization	+		-					
Sheet Naming	+	+	-					
Drawing Sheet Templates		++	-					
Suggested Color Coding for MEP			++		+++			
Presentation Styles								
Annotation	++	++						
Text Assignment	++	++						
Line Weights	+							
Line Patterns	-							
Line Styles	-							
Hatching and Filled Regions	-							
View Templates	-							
Dimensioning	++	+						
Drawing borders and Title Blocks	-							
Symbols	-	+						
Copyright (Splash Sheet)	++							
Resources								
Software		+	+		+	++	+++	+
Hardware		+			+	++		
IT Upgrades		+						
BIM Content / Resource Libraries	+							
Keynotes	-							
Custom Metadata	-							
Keyboard Shortcuts	-							

New guideline by Architectural BIM Promotion Council

The MLIT summarized the status of BIM use in 2019, stating that although a considerable number of architectural firms are showing interest in introducing BIM, the actual use of BIM in practice remains low. Even BIM projects utilize it only within each discipline. Thus, the consistency of information, the virtue of BIM, is not secured. Furthermore, the penetration of BIM up to the maintenance management stage is yet to be accomplished [158].

In March 2020, Architectural BIM Promotion Council under MLIT released "Guidelines for BIM Standard Workflows and Their Application in the Construction Sector (Version 1) [159]." The 2014 BIM Standard was designed for use in government repair projects where BIM is applied. This Guideline is considered to have a broader scope of use and is a de facto replacement for many practitioners. However, the government has not clarified the reciprocal positioning with the previous guidelines.

The new Guideline explains that the advantages of BIM utilization are limited due to its use only within the current design and construction process. The document outlines that a cross-process use of BIM, in which models are passed on and used continuously, can further increase the benefits of projects. At the same time, however, the Guideline also states that the benefits to the client are currently unclear.

The content has been more than doubled compared to the former guidelines. The majority of the content is devoted to defining workflows, divided into five major collaboration patterns among project stakeholders to achieve model delivery, and explained individually. In addition, it describes in detail what should be added to the current contractual agreements concerning BIM. In addition, it briefly mentions that the level of detail in the model should be isolated from the drawing definitions, that 2D annotations are appropriate while setting the appropriate LoD for the project, and that the technical cooperation of specialized construction companies is also essential.

In addition to the above, the call for public comments on the report's release included comments on the BEP/EIR, the need to add necessary descriptions to the workflow, and the need to enhance the benefits based on specific examples such as the results of model projects. However, the following extremely relevant topics will not be addressed in the second edition: design options, BIM manager, compensation for variation orders, the definition of the as-built model, and intellectual property rights [160]. In these respects, 2020 MLIT guidelines are almost devoid of advocacy elements showing their opportunistic perspective. It is noteworthy that these topics have been judged as "further discussions needed due to the various opinions." Although they can bring a unified view to the confused field, the stance of not including them in the guidelines until the views of the field are fostered is somewhat far from the stance expected of government guidelines. Rather than prescribing the orientations, they are more likely a dictionary for what is generally agreed in the field.

Other BIM protocols

Japan Institute of Architects (JIA) issued a BIM guideline in July 2012 [161]. As the foreword states, this protocol focuses on the concept and potential use of BIM. JIA BIM guideline covers: desirable BIM organization, expected roles of stakeholders, potential BIM uses in project phases, basic regulations in data exchange, primary rules in libraries, potential BIM uses in engineering and quantity survey, BIM cost, BIM and urban information, and deliverable. JIA BIM guideline provides much more extensive coverage than the MLIT guideline, and it supplies a more specific workflow along the project timeline. It is meaningful that the guideline states the standard scope of work for individual project members and the basic concept for intellectual property rights. Although the guideline supposes the reference by architects, including the structure and MEP engineers, there is a comprehensive overview of the contractor's BIM benefit and expected use to overcome the joint-loss between the design and construction stage. The guideline also contains the software list for BIM authoring tools and simulation tools. However, this JIA guideline does not provide the standard for data structure or the naming convention for LODs. BEP is also not explicitly mentioned in the JIA guideline.

Another is the Standard Process Map for the BIM Project issued by the Architectural Institute of Japan [162]. The document is the interpretation of the Information Delivery Manual authored by the International Alliance for Interoperability. The document contains the process map part of IDM to contribute to facilitating BIM implementation in Japan. In addition to the translation, AIJ Standard Process Map customizes the original to fit the commercial convention in Japan, especially the scope of work for each discipline. The document is available online, and it also covers the LoD definition. This LoD is to regularize the depth of work with referring Model Progression Specification V08-08-20 by AIA. Separately, Hirano et al. overviewed the interpretation of LoD by interviewing a few architect offices and general contractors, concluding that further arrangement is required for efficient application to the local context [163].

Japan Federation of Construction Contractors (JFCC) has been working on centralizing the knowledge on BIM implementation by contractors and builders. After multiple publications for construction BIM, the summary of construction BIM in Japan was made available in November 2017 [164]. The summary provides a concrete example of implementing BIM in construction projects based on the survey for the early-adopter construction firms. This JFCC guideline is much more practice-oriented. It includes multiple case studies for tackling the BIM issues on low-hanging fruits, hardware environments, organization, education, and costs.

Several publications contain the templates, yet the above-mentioned BIM Protocols do not provide the model template data. AIJ made the BEP template available online, with good coverage for BIM projects [165]. It is not yet the stage that such templates are openly exchanged or distributed among many AEC practitioners.

Summaries from fact-finding surveys

BIM adoption rate

The Ministry of Land, Infrastructure, Transport and Tourism (MLIT) investigation in 2021 [166] is the latest government fact-finding survey about its use in the Japanese building and construction industry. Among 813 respondents from 2,363 targeted AEC firms belonging to 13 major domestic industrial associations, the result depicted that 46.2% had already implemented BIM. The general contractors represented by 117 participants marked the highest ratio of BIM adoption as 81.2%, followed by the architectural design firms (58.4%). Smaller organizations lagged in introducing the environment; the implementation rate was reported as 87.8% for organizations larger than 5,000 employees, while it ranged from 20.0 to 36.7% for the firms smaller than 100 employees.

Another statistic in 2019 by the Japan Association of Architectural Firms [167] surveyed the belonging 955 architectural design offices, including design departments of builders or general contractors. The result revealed that 17.1% of respondent firms answered that the BIM is in practice; it only reaches up to 30.0% even including the companies introduced yet not brought into the actual project. The most frequent answer for the number of BIM-skilled employees in respective offices was only one (33.9%), followed by two (21.3%).

A questionnaire conducted by LIXIL, a major building material supplier, was reported on March 2021 [168]. The 931 respondents majorly work under relatively small organizations; 64.1% are from firms with less than ten employees. Potentially due to this nature, the BIM implementation ratio was shown even lower than the above as 22.4%. Similarly, the organizations with more than 200 members exhibited a higher percentage of 43.8 than the average.

Overall, it cannot be concluded that BIM has become a platform for most industry professionals. All research displayed the tendency that the organization size correlates with the adoption rate. It is vital to motivate smaller offices to introduce the BIM environment by preceding BIM adopters.

Preferred BIM software used in the sector

Having said that, BIM does not signify model creation. The applications to create building models undoubtedly occupy the core role in BIM workflow. Revit by Autodesk and Archicad by Graphisoft (a part of Nemetschek) are the two top products that are broadly used internationally. UK BIM Survey 2019 reported that 70% among 988 researched UK-based organizations listed Revit at the top of the model and drawing production software, followed by Archicad (15%) [169]. 2018 Construction Technology Report by JBKnowledge demonstrated the dominance of Autodesk product in the United States that 40.1% replied Revit as the most preferred BIM software, while Archicad only hit 1.3%, which was as low as other products such as Bentley (1.9%) or Microstation (1.9%) [170]. The Japanese practitioners have a different tendency as reported in the survey by JFAA [167]; Archicad is the most adopted software (43.0%), followed by Revit (33.2%) and GLOOBE, the local software specialized in shop drawing production (17.5%, multiple answers allowed). The plausible reason for this preference was the active localization of Archicad when Graphisoft entered the Japanese construction sector, which resulted in the swift expansion of the share in the market.

Although the statistics for sales or the number of issued software licenses are not publicly available, It is highly speculated that Revit gains the most attention among the available BIM software worldwide. Boiko attempted to demonstrate the most popular BIM program by Google search volume index. It demonstrated that Autodesk Revit had compelled other competing applications like Archicad, Tekla, Vectorworks and Allplan over 15 years until 2020 [171]. While the availability of log information and relevant preceding research adopts Revit as the primary subject, the selection was also supported by these facts that Revit has become a de facto standard of the global AEC industry.

Positive effect on implementing BIM

The motivation to alter the existing workflow and feedback for effect was analyzed in the MLIT survey. 72.3% of BIM-ready firms answered about their motivation for implementation to anticipate future trends in the industry. Among the BIM companies that were encouraged by their competitors, 80.2% evaluated the effect of BIM positively. This tendency reflects the cooperative business environment in Japan. The role of large private enterprises is considered to play an extremely important role, particularly the general contractors providing design and build services because they exert a large influence on industry trends with the potential as a hub of ordering and receiving relationships.

Expectation to the government role

The National Building Standard in the UK made another international comparison in BIM implementation. NBS International BIM Report 2018 [172] revealed the high awareness of Japanese respondents toward BIM, which was as high as other surveyed countries except for the Czech Republic. The ratio of BIM use in actual projects was also equivalent to other regions. There is, however, a strong contrast in the people's attitude to the government. Only 17% of Japanese respondents answered that the government is on the right track with BIM, significantly lower than the UK or the Czech Republic, 54 and 31 percent respectively.

Perceived shortage of skilled personnel

Another industry-wide poll was done by the Architecture Institute of Japan (AIJ). Research Committee on Information Systems Technology carries out a biennial survey of architect firms and contractors. According to their 16th report published in February 2017, the most massive problem in BIM use was the designers' inability to use BIM and the time required to master it [173]. The lack of industry-wide protocol standardization ranked fourth in the architect group and third in the contractor group. On the other hand, the percentage of corporations that already implemented MLIT BIM standards remained 5% among 93 respondent firms in total. The expectation on BIM delivery to the Government stayed low (19.5% in architect group, 9.1% in contractor group), despite other items such as the improvement on multidisciplinary data sharing (68.3%, 58.2%) or the automated quantity takeoff (36.6%, 40.0%) marked high number. Another perspective is understood from the question, which asked if the respondents refer to other projects' case studies shared in seminars. The sum of answers for "do not know," "not informative," and "informative, but not directly applicable to our environment" reached up to more than 70%.

In the 2017 JFCC survey, almost all survey respondents identified the lack of human resources as a problem in BIM promotion [164]. The AIJ survey also listed the lack of human resources as one of the main reasons for problems in BIM promotion [174]. Overall, the shortage of BIM human resources exceeds the need, and organizations to alleviate the situation by training permanent staff, widening the gate for new graduates, and increasing external human resources. However, the BIM curriculum is far from complete even in university education.

Findings

The Japanese government has addressed BIM development for more than a decade. MLIT published a BIM guideline to encourage the practitioners' voluntary BIM use. However, the number of public BIM projects is not steadily increasing so far.

MLIT BIM guideline places importance on consistency with the existing regulations. While the area for designers or builders to configure the BIM plan remains significant, this should lower the project tenderers' barriers. While the whole BIM Protocol remained inconclusive, architects and builders may hesitate to take the initiative in proceeding with the public projects.

Practitioners' interest in BIM is high. They express concern about BIM use in projects because of the education system and human resources. Although the MLIT BIM guideline is reasonably known, only a few firms implement it to the project. They expect to share the BIM model data with other parties. They often reject learning from other case studies since they consider their ecosystem different from others.

Japan recognized that enhancing the BIM workforce would resolve the issue. Therefore, they seek skilled BIM users or established education systems to train in-house staff. However, developing universal BIM Protocols will facilitate BIM training and data exchange. While other BIM Protocols are available, the Protocols focus more on management strategy than practical information. Instead, individual companies have developed their BIM Protocols to accumulate their findings internally.

The Japanese university education does not put importance on BIM yet. 3D modeling became popular today though, very few colleges in Japan have BIM in architectural curricula. It is gradually becoming common to seek the modeling of human resources in overseas countries such as the Philippines, Vietnam, or India, to resolve the urgent need for BIM operation.

Cultivating a universal Japanese BIM Protocol resolves multiple factors. Although the know-how has been kept at the individual corporate level, it is gradually disclosed for open use. Taisei Corporation has distributed its door and window Revit components free of charge since 2015 [175]. Nikken Sekkei Digital Design Lab (DDL) launched a website titled OpenDDL [176] to share its findings. The movement to build a versatile BIM knowledge base is highly expected.

The Japanese AEC industry shows high interest in BIM, and the use of BIM has become popular over the past decade. Although there are multiple BIM Protocols available in Japan, they are not a driving force to resolve the BIM issues people experience in projects.
Multiple surveys revealed that the BIM workforce is perceived as the most massive problem in BIM implementation. However, there is room for improvement in spreading useful BIM Protocols to resolve the practitioners' BIM concerns. Considering the Japanese building and construction ecosystem, developing industry-wide BIM protocols is highly needed to grow BIM skills for the future.

Preparatory Study 2: Discovery from Open Discussions

This section attempts to extract issues from topics in discussions on BIM to collect a wide range of challenges and extract issues that have often been overlooked in the past. The author organized the events as part of the preparatory meetings to establish a novel academic society named Architectural Informatics Society.

The association aims to reconstruct the concept of "architecture" from an informatics point of view as a consciousness of humankind's continuous creation, construction, and utilization of artificial environments. Its mission is to contribute to the community through open discussion, accumulation and dissemination of information, and support for human resource development to share and systematize knowledge about the relationship between information theory and architecture and urbanism, which is crucial for the world of tomorrow [177].

In establishing this new community of architectural informatics, it was imperative to investigate how practitioners and educators would be concerned with the field. For that purpose, the preparatory meetings were held six times, opinions were collected in various ways, and the results were published online to foster further discussion. Here, the author summarizes the opinions from the second and sixth workshops, where he served as an organizer to reinforce our understanding of the issues.

Workshop 1: Open discussion for BIM, opportunities and challenges

The second event featured an open discussion on the use of BIM. The session was held in Tokyo on May 14, 2018, with over 130 physical participants and dozens of online participants. The event was led by the author and Yukie Hirashima, a BIM consultant from Autodesk, who answered a range of questions and opinions about BIM. The event was reported in detail on the website of 10+1 [178]. The picture taken at the event is shown in Figure 10.

Figure 10. A scene from the open discussion.

While announcing the outline of the event, questions related to the theme were collected through Google Form in advance. This resulted in 43 posts from the participants. As an ethical consideration, anonymous submission was possible. The questions were kept under the serial number from Pre1 to Pre43 to avoid any detriment to the questioner. In addition, questions were accepted during the event sessions and the discussions, resulting in 35 questions. These were given the numbers from On1 to On35. As the discussions and questions were in Japanese, the author translated them into English for inclusion in this paper.

The questions received can be broadly sorted into eight categories. Many participants seemed knowledgeable about BIM, and some asked about practical problems they were already facing. These questions were mostly observed in the Standardization, Technical aspect, and Workflow categories. Some practitioners who were not aware of BIM but had not put it into practice raised questions about their problems and doubts in the Implementation and Advantage categories. Table 2 shows each category and the questions that belong to them.

Table 2. Categories of questions raised for the BIM open discussion.

Category	Selected questions from participants
1. BIM implementation	● What is the difference in the degree of penetration and acceptance between Japan and other countries? ● What are the current project criteria for determining whether BIM should be used? (scale, program, construction period, etc.) ● Will design firms that do not adopt BIM be able to survive?
2. Career development	● I'm a 50-year-old designer. Can I get by until retirement without learning BIM? ● If you were to leave your current company and start your own, what kind of business would you create as a BIM specialist? ● Looking at BIM as a workflow, are there any job skills essential to properly manage it? Also, what skills do you think will be essential in the future? Are these skills required as a designer, engineer, or individual job function?
3. Collaboration	(Detailed in the separated table)
4. Standardization	(Detailed in the separated table)
5. Education	● "I don't think students will learn how to really handle BIM. I think it often becomes just modeling software. I want to know how students will be taught BIM, which is a software of practice." ● I am a student who recently started learning BIM. What things should I be aware of to help me in my future career? ● I am a student in Kyoto. I'm currently using Archicad, but I'm not able to use BIM to its fullest; I can only create 3D models. What kind of training should I do to make sense that I am using BIM instead of using 3dcad? What would be your priorities for that training?"
6. Technical aspect	● Please compare the strengths and weaknesses of the primary BIM tools, Revit, Archicad, and Digital Project. ● The floor area ratio and building footprint ratio are very important in practice, but it is extremely difficult to calculate them by default. I use Revit up to the point of tabulation and then process them in Excel, but I don't think that is the best way. To what extent should we use Revit, and to what extent should we use API or Dynamo? ● How do you ensure the security of data in BIM projects? I would like to know the reality of current operations and challenges. Is there a need for information security knowledge in BIM and building informatics?
7. Workflow	● In the case of non-BIM projects, the history of changes has been handled daily through minutes or reports and redactions until the changes are substantial enough to update the drawings. How about the case in BIM projects? ● How do you deal with BIM data after the project is over? ● Is there a role that BIM can play in minimizing contractual changes from the client?
8. Advantage of BIM	● What do you personally enjoy most about being involved in BIM? ● I suspect that BIM is not a tool that everyone can benefit from. Is it a tool that benefits everyone, or is it a tool that is specific to certain needs? ● There seems to be a lot of emphasis on convenience, such as increasing efficiency and capturing data, and I feel that the 'fun', 'creativity', and 'freedom' of using BIM are missing.

There were eight questions related to the standardization (Table 3). None of them directly pointed out inadequacies in BIM Execution Plans or BIM Guidelines. However, these questions instead addressed the lack of industry-wide standard information from two perspectives. One is the lack of standard procedures in BIM (Pre21, Pre23, Pre34, On24), which is causing difficulties in BIM practice. The other is that the shortage of archives of off-the-shelf products and standard details leads to an increase in the scope of architect's work, thus preventing the effectiveness of BIM from being experienced (Pre17, On7, On14, On15).

Table 3. Questions categorized under "4. Standardization."

#	Question
Pre17	There may be some companies that are creating proprietary BIM tools from scratch. In this genre that deals with information, is there a concept of open source rather than company-based development in this genre? Do you think this is necessary?
Pre21	How do you deal with the difference between the ideal model and the practical way of calculating the area? Also, how do you think the software supplier side should deal with such discrepancies?
Pre23	The position of information coordinator is necessary. The practitioner must also serve in this capacity, and it seems to be a heavy burden. To reduce such workload in the future, I think that an information system for architecture is also necessary for practitioners, and I would like to ask you about your outlook on these points.
Pre34	Will the design drawings disappear in the future?
On7	Will people use BIM objects even if provided as a paid service? We believe that we should provide them as a manufacturer, but we have not found any direct benefits at the moment.
On14	To use BIM in Japan, it would be difficult without using product libraries such as joinery and sanitary facilities from manufacturers.
On15	How about a platform where you can search for details of Japanese architecture?
On24	You commented on the difficulty of converting the area into information in BIM. Are there any other "spaces" in an architecture other than "mobs" that you feel are difficult or frustrating to inform?

Nine questions were posed regarding the collaboration category (Table 4). Some questions were about project stakeholders' disinterestedness as an inhibiting factor for BIM adoption (Pre2, On9), and the other was for the labor division within the project team (Pre3, On4).

A group of questions that deserve special attention is related to the modelers (Pre29, Pre35, On34). These questions all refer to the role of the individual providing modeling workforce for projects. Pre29 specifically asks whether it is acceptable to ask outside personnel or subcontractors to do the modeling. On34 explicitly seeks a means to resolve the lack of BIM knowledge on the part of employees themselves due to the reliance on external personnel for BIM promotion. These questions are closely tied to the problem of solving the shortage of BIM specialists that we have seen so far. Due to the limited time to acquire BIM skills, BIM tasks are easily outsourced to external specialists. Nevertheless, this situation rather causes apprehension to the employees.

On3 is also worth mentioning: it is described as "scary" for an unskilled BIM person to access a BIM model created by others. This could be interpreted in two ways: the fear of not being able to self-assess the risk of making unwanted edits to the model created by an expert, or the risk of damaging the data and negatively impacting the progress of the project. The other is the uncertainty to formulate measures to remedy the situation when the project's BIM progress turns out to be not as observed from the outside.

This opinion in On3 could augment the views in On34. When specialists are deployed to promote BIM, the BIM-related tasks can easily be entrusted to them. Once the model is developed to a certain extent, it exceeds the understanding and imagination of non-BIM practitioners; thus, they become "afraid" to access it. Therefore, practitioners become increasingly detached from BIM, and they continue to be uncommitted to BIM.

Table 4. Questions categorized under "3. Collaboration."

#	Question
Pre2	I believe that BIM is being promoted especially in organizations, but what are the advantages of using it in small companies and studio offices?
Pre3	What is the best way for a BIM manager and a project manager to collaborate, and with what kind of relationship?
Pre10	How are the design and construction sides using BIM and how should they be using it?
Pre29	Who handles BIM, internally or externally?
Pre35	Who should create the BIM model?
On3	Why is it "scary" to open a model created by someone BIM talented?
On4	What is the minimum project size where you need a BIM manager?
On9	I don't know how to convince people that it is difficult to keep using the same model from design to construction (they say that should be the advantage all along).
On34	When BIM models are input by outsourcees, I, the designer, cannot use BIM at all. I don't have much time to practice. What should I be able to do first?

Workshop 2: Roundtable for "making a textbook for Architectural Informatics"

The sixth event was a roundtable discussion to envision a new architectural informatics discipline and conceptualize a textbook to structure the subject matter and render it communicable. It was held in Tokyo on February 3, 2019, with over 100 physical and dozens of online participants. Statements and summaries are available on the website [179] (Figure 11).

The facilitators were Yasushi Ikeda, Professor at Keio University and Keisuke Toyoda from Noiz Architect. The panelists included Tsukasa Ishizawa from Takenaka Corporation, Toshikatsu Kiuchi from his architectural planning office, Daisuke Tsunoda from Nikken Sekkei Digital Design Lab, and Junichiro Horikawa from Orange Jellies. Also invited were Haruyuki Fujii (All Professor, Tokyo Institute of Technology), Shun Watanabe (University of Tsukuba), Yasuto Nakanishi (Keio University), and Kazuo Mitsui (Nihon University) as guest commentators from academia.

Figure 11. A scene from the roundtable discussion.

In this discussion, the panel proposed several configurations for the proposed book, then discussed the viability of each structure and the anticipated issues in using it for education at universities. Based on this discussion, a publication for the broad audience, "Toward Architectural Informatics," co-authored by the authors, was released on December 25, 2020 [180].

Given that most conceived topics are new to architectural education, the discussion explored when to start teaching students and how to incorporate them into the curriculum. Watanabe pointed out that design practice forms the core of conventional architectural education, with various professional education programs supporting it. Fujii commented that it would be challenging for students without learning the basics of programming and computational geometry before teaching architectural informatics. Nakanishi opined that computational aspects are not necessarily essential for architectural informatics, just as architects are mostly interested in social aspects and others prefer sculpting.

Establishing new classes on building informatics in a limited curriculum is hard. Few colleges or universities provide sufficient time for instruction on modeling how-tos. A university student remarked that there was an assignment to work on parametric design, where 30% was spent in class. As Mitsui highlighted, Japanese architectural courses, including engineering programs, encourage students to become licensed architects.

Toyoda remarked on a collaboration demand for architectural expertise from outside the domain as a threat occurring in reality. Still, the absence of informational knowledge and communication channels in the architecture industry has created barriers, which is a serious problem. Nakanishi commented that students equipped with architectural informatics skills could work for the video game industry, film production, or video design.

As seen above, teaching architectural informatics, including BIM, in universities persists to be a great challenge. The absence of literature to establish the field is one of the main factors though, the lack of corresponding departments, lectures, and educational systems further complicates the situation. Besides, from a practical point of view, the industry demands more emphasis on content that leads to architects' certification. At present, the building information could be regarded as an accessory position.

It is commonly believed that younger generations are more likely to adapt to information technology. The tendency is generally true partially because experienced practitioners do not desire to change their working practices. However, it is not advisable to expect students or young practitioners to master BIM within their working hours. As seen in the previous section, it is unlikely that practitioners will voluntarily take the time to learn the new software.

It implies that disseminating a strong need for BIM-oriented education from the practical side is integral to transforming university education. Still, as seen in the earlier question, learning realistic workflows from an early stage does not automatically equate to educational excellence. Teaching only modeling skills is insufficient from a collaborative perspective. Besides designing models, it is vital to draw a portrait of the profession we should strive to become for future architectural information education.

Summary

This chapter outlines the author's preparatory research findings and activities that reinforce the thesis premises.

In the study on BIM guidelines, it was recognized that the information available for industry-wide use in Japan exists yet is poor in content, and most details are left to practitioners' decisions. It seemingly provides a greater degree of freedom for practitioners. However, as can be seen in the workshop questions, the reality is that it has led to confusion among professionals. The lack of applicable information as an industry standard has hindered the introduction of BIM.

The problems were extracted from the open discussion and the round table based on architectural practice and education. It should be reiterated that the human resources engaged in modeling are not self-evident. Due to the lack of knowledge and experience in BIM, practitioners outsource the work to external personnel. Despite the expectation that the BIM talent pool will grow among the younger generation, academic educators argue that the current education system emphasizes acquiring architectural qualifications and that building information education only adds to it. It indicated that the BIM workforce would not be alleviated spontaneously, and thus, the industry must stress the need for such enhancement.

Therefore, observing the collaboration in practice and describing the figure of the desired person is essential. The subsequent chapters will discuss the exact methodology and the analysis results conducted with the data.

Chapter 5: Theoretical Framework

Overview

This chapter establishes a conceptual framework for this thesis. The design science research method for information systems was adopted as the foundation of the research process. Since the partitional clustering algorithm forms the core of the design and development phase, the plausible algorithms and the validation factor are introduced. The term-weighting factor, optionally explored the normalization process, is also briefly introduced. The selection of the estimator was jointly discussed in the following chapter. Visual analytics is indispensable to decipher and assess the content of the BIM log for the laypersons to find the weaker signal patterns inside the records. The application of this concept was greatly influenced by the preceding proposal termed the mathematical model of meaning. Finally, the concept of keystone species from its origin and the application in a broader context was examined to interpret it into the AEC ecosystem.

Design Science Research Method

The research flow is based on the standard design science research method (DSRM) for information systems (IS) [181]. Design science is the epistemological basis for the study of what is artificial. Design science research is a method that establishes and operationalizes research when the desired goal is an artifact or a recommendation. In addition, the research based on design science can be performed in an academic environment and an organizational context [182]. Design science research aims to study, research, and investigate the artifact and its behavior from an academic and organizational standpoint [183]. It is a research method focused on problem-solving [184]; the methodology suits the purpose of investigating the BIM log as an artifact and its behavior through the collected information.

The research is structured by a design and development-centered approach. As the core of the thesis, the author aims to design and develop the algorithm and method to decipher and analyze the BIM log information collected from various types of organizations. The design science research artifact will be deployed to large organizations in the Japanese AEC ecosystem.

As the problem identification and motivation, the lack of insight into the project BIM activity was found to keep non-BIM practitioners away from project BIM workflow. As the government did not handle the BIM initiative, influential players in the industry should play a central role in spreading BIM industry-wide. Because the reliance on external BIM technicians is a norm, discovering the key players inside the large organizations is an urgent matter to build a role model for smaller firms and the educational field.

The need to identify such keystone players requires a data-driven system. The BIM log was selected as the solution's objective from the preceding studies. Algorithms were selected based on the collected project logs in the design and development phase, which compose three separated datasets. Through the demonstration, the visualization was explored through the empirical steps per dataset to depict the traits of BIM activities at different levels such as organization, project and individual. The additional information evaluated the findings from the respective data donors. Iterations were made over the empirical studies; visualization and the data coverage were further enriched as the research progressed. Finally, the academic publications made the communication as a dissertation thesis.

The conceptual diagram for this research framework is illustrated in Figure 12.

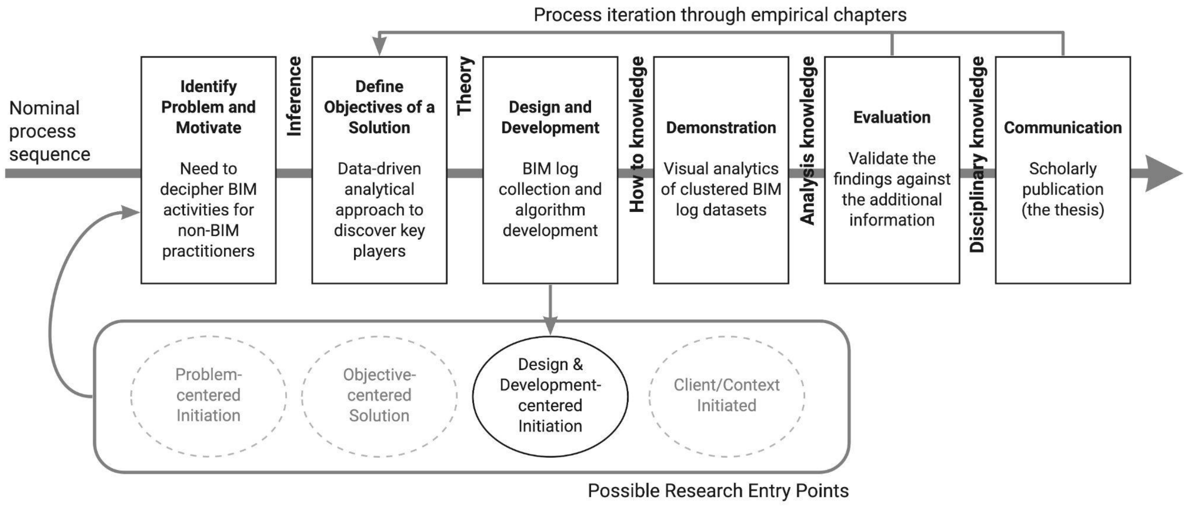

Figure 12. The research framework based on the design science research method (DSRM).

Partitional Clustering Algorithms and Validation

Finite mixture models have been widely used in cluster analysis over the last several decades; however, their first application dates back to more than 120 years ago [7]. Model-based clustering is a popular technique relying on the notion of finite mixture models that proved efficient in modeling heterogeneity in data [185]. The algorithms are deployed to the tailored Python script by Scikit-learn, a Python module that integrates many state-of-the-art machine learning algorithms [186]. Among the coverage of the package, two estimators are shortlisted for the clustering purpose, namely, K-means and VBGMM. Brief introductions of these clustering techniques are given.

The k-means algorithm is likely to be the most commonly used for initialization. The k-means algorithm divides a set of $\boldsymbol{N}$ samples $\boldsymbol{X}$ into $\boldsymbol{K}$ disjoint clusters $\boldsymbol{C}$, each described by the mean of the samples in the cluster. The k-means algorithm categorizes data by separating samples in n groups of equal variance, minimizing a criterion known as the inertia or within-cluster sum-of-squares. The K-means algorithm chooses centroids that minimize the inertia or within-cluster sum-of-squares criterion. This results in a partitioning of the data space into Voronoi cells. The means are commonly called the cluster "centroids"; they are not generally points from, although they live in the same space.

$$\sum_{i=0}^{n} \min_{\mu_j \in C}(||x_i - \mu_j||^2)$$

A Gaussian mixture model is a probabilistic model that assumes all the data points are generated from a mixture of a finite number of Gaussian distributions with unknown parameters. One can think of mixture models as generalizing k-means clustering to incorporate information about the covariance structure of the data and the centers of the latent Gaussians. Variational inference extends expectation-maximization that maximizes a lower bound on model evidence instead of data likelihood. Although the principle behind variational methods is the same as expectation-maximization, variational methods add regularization by integrating information from prior distributions.

The performance of the discriminability should select the algorithm. If the ground truth labels are unknown, the evaluation must be performed using the model itself. Among possible state-of-the-art methods, the silhouette is a potential formula for evaluating the consistency of data clusters in the partitioning problem. The silhouette analysis allows evaluating the methods that create better tightness and separation.

The Silhouette Coefficient is defined for each sample and is composed of two scores. Given the mean distance between a sample and all other points in the same class as ***a*** and the mean distance between a sample and all other points in the next nearest cluster as ***b***, the Silhouette Coefficient s for a single sample is then given as:

$$s = \frac{b - a}{max(a, b)}$$

Values range from -1 to 1; the closer the value is to 1, the sample displays a better match to its own cluster. When the value is near 0, the sample is close to the boundary of the clusters. The value closer to -1 offers that the sample may be misassigned to another cluster [187].

Term-Weighting Factor (Optional)

A term-weighting factor was optionally applied to the database to enhance the clustering result. Term frequency-inverse document frequency (tf-idf) is a universal numerical statistic that reflects the importance of the terms in a corpus that are often used for information retrieval and text mining [188]. Term frequency, tf(t,d), is the frequency of term *t*, where $f_{t,d}$ is the raw count of a term in a document, i.e., the number of times that term t occurs in document d.

$$\mathrm{tf}(t, d) = \frac{f_{t,d}}{\sum_{t\prime \in d} f_{t\prime,d}}$$

Some commands are repeatedly and commonly issued, such as ID_EDIT_MOVE (to move objects) or ID_ALIGN (to align the object to other selection), and appear in most logs. These commands are too generic to surmise the activity context. Additionally, as users often issue them hundreds of times more than other commands, they can strongly influence the clustering estimator resulting in the degradation of the discriminability of the machine learning process. After applying tf-idf, the counts of general commands are offset and commands uniquely found in specific users increase proportionally.

Visual Analytics and Mathematical Model of Meaning

The collected log files are transformed into a data space with an overwhelmingly high dimension. Since the BIM users execute specific commands along with their aim under a sequence of tasks, dynamic contextual understanding of data is crucial to examine their contribution to the projects. In this study, the authors aim to expand the dataset collected from multiple organizations and apply visual analytics to empower mining with extended scalability [189].

Visual analytics is the science and practice of analytical reasoning by combining computational processing with visualization. Developing the long tradition of using visualization to help interpret computed results, emphasizing the benefit of an iterative cycle of computations, understanding and evaluating the results to refine the analysis or investigate complementary findings. One of the important principles of visual analytics is not taking computational analysis results for granted [190].

Visual analytics has been tested in the field of log mining. Yoo et al. proposed a novel visual analytics system, LongLine, enabling interactive visual analyses of large-scale audit logs [191]. Business Intelligence (BI) is a frequently referred concept enabling storytelling. Elias et al. explored the actual practices through in-depth interviews with expert analysts and reported recommendations [192].

Referring to the comprehensive review made by Zhang et al. for the commercially available systems [193], Tableau was adopted for the visualization process. Tableau is a widely adopted BI solution in the industries; it enables users to test many different data filters and groupings to discover the critical command pattern with the graphical outputs for comparison purposes.

The interpretation process is highly influenced by the concept of the mathematical model of meaning (MMM) proposed by Kiyoki et al. It is the metadatabase system for extracting appropriate outputs according to the user's impression and the contents [194]. The data as a set of words accompany features to construct a data matrix. After the normalization process, we obtain the orthogonal semantic space, where vectors map the data. The user's impressions or the image contents are given as a context represented by a sequence of words; it forms a subspace of the orthogonal semantic space. The MMM concept is applied to *Kansei*, a concept including emotion, impression, feelings, psychological or physiological reaction, the semantic associative search, which includes sensitive recognition. Kiyoki et al. designed the "Five-dimensional World Map System" as a multimedia semantic computing system for global environmental analysis [195].

MMM is a database that supposes words; data entries can have an infinity of meanings. It regards data semantics as dynamic; the eqdata's uality, similarity, and relationship are dynamically calculated according to the context and circumstances. The visual analytics process involves human interpretation of visually represented outputs and decisions concerning the next steps.

Keystone Species

A keystone species is an entity with a disproportionately large influence on an ecosystem compared to its abundance. Similar phenomena can be witnessed in the internet and software systems. This concept has been applied in various web services [196], [197]. To identify users with a semantically strong influence on the projections, use both of them as metrics. Machine learning in BIM log mining should be suitable for discovering weaker signals.

For the definition of keystone species, we use the population density *pi* occupied by species *i* in the ecosystem and the impact *Ii* when *i* is removed from the ecosystem. The impact is defined as how a quantitative value representing the nature of the ecosystem, such as the population of all species in the ecosystem, will change before and after removing the species *i*. Let *tN* be the quantitative value representing the nature of the ecosystem before removing species *i*, and *tD* be the value after removal. The impact *Ii* of removal of the species *i* is shown below[198].

$$I_i = \frac{t_N - t_D}{t_N}$$

BIM specialists are often appointed separately from the architects, such as BIM modelers and technicians. Prior research on BIM staffing focused on identifying the type of person required in the market based on job descriptions [125], [148], [149].

In Japan, licensed architects usually hold responsible positions for client meetings, governmental consultations, et Cetra. The abovementioned government survey revealed that BIM practices are carried out by licensed architects and by supplementary personnel without licenses, particularly in the mechanical and electrical disciplines[166].

The project will not progress with only BIM operators in place. Their tasks need to be supervised and approved by qualified designers. Experienced architects may prefer to review the model in drawings to exercise their expertise. However, it only remains a partial optimization to check the model's progress through drawings. Decisions about the effectiveness of model work and information build-ups in the model are also necessary, which are deeply related to the project requirements. Non-BIM designers should also possess adequate BIM knowledge to facilitate this communication. Many practitioners' skills and knowledge of BIM generally fall behind due to the educational costs and the lack of awareness [91]. Meanwhile, there exist some successful projects utilizing BIM. Social network research of BIM projects showed that only a limited number of personnel are engaged in modeling [122].

In the case of resource extraction and provision, a few disproportionally large transnational corporations dominating the system have been described as a keystone pattern [199]. As the driving players of the phenomenon, they may be considered keystone actors in global social-ecological systems [200].

Ejima et al. define the keystone species as a set of species that significantly impacts the ecosystem if removed from the system, irrespective of its small biomass. From the perspective of social activities, the stability of ecosystems is realized by keystone species' high level of activity and engagement; thus, identifying them may work to increase the community's activity. An attempt to identify a small group of key players in the BIM project who silently yields a great positive influence to project BIM progress may be interpreted as the method to discover *keystone BIM players*.

Summary

This chapter first presented the design science research method for information systems to form the mainstream of the thesis. A design and development-centric approach focusing on the collected BIM logs as the artifact was adopted for the initial motivation. After solidifying the objective and solutions, the demonstration and evaluation iterates for rounds through the empirical studies, expanding the scope and data coverage. A few indispensable theories are implemented: the partitional clustering algorithms, term-weighting factor, visual analytics and mathematical model of meaning, and the concept of keystone species. The concrete methodology for the design and development phase is elaborated in the next chapter.

Chapter 6: Methodology

Overview

This chapter provides the details of the research methodology. After introducing the subject log data, the data collection is elaborated to clarify the configurations of three different datasets for step-by-step exploration in the empirical chapters. A python script was utilized to transform the unstructured information into the database. Next, the clustering algorithm was selected by the result of data separation. Since the log only partially reflects the project activities, the supplemental data was prepared to overcome the drawbacks of focusing on a specific software platform. The concept of combined datasets is depicted in Figure 13. Finally, the ethical consideration made for the above process was briefly summarized.

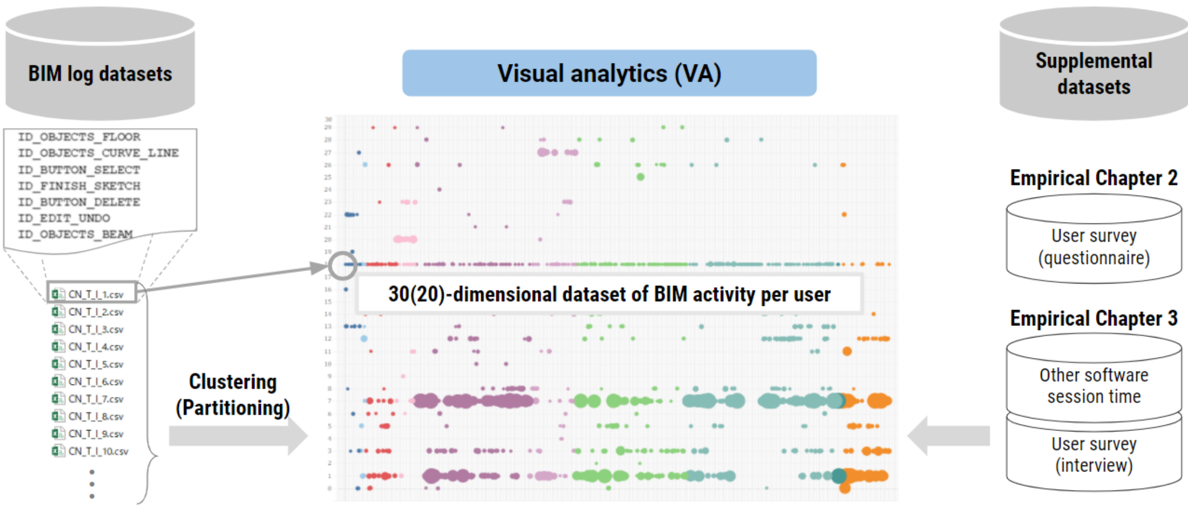

Figure 13. Overview of research design.

Data Collection

The subject of the analysis was the event logs, called journals, produced by Autodesk Revit. A single journal file captures the actions taken by the software from the beginning to the end of the software session. Though the journal was initially intended to troubleshoot technical problems with the software [201], past studies proved it serves the process mining purpose as it contains rich enough information to track the details of user activities. Moreover, as Revit is a globally adopted BIM authoring software, journal files are ideal for collecting information from multiple disciplines and regions. The records were collected to construct three different datasets for the empirical study. Table 5 presents the details about the respective datasets.

Table 5. Details of the collected datasets.

	Dataset 1	Dataset 2	Dataset 3
Number of organizations	1	10	2
Number of data donors	7	37	182
Number of collected log files	7	1,299	8,432
Issued commands (effective*)	4,684	226,383	565,289
Issued commands (overall)	5,990	622,793	1,113,977
Average issued commands per log	856	479	132
Collection Period	August 2018	February – May 2018	April – August 2019
Method	Submitted after the modeling workshop conducted by the author	Manually transferred either by email or file storage server	Automatically transferred by the installed batch program

Dataset 1

The first dataset comprises log files collected under normalized conditions that allow the cross-comparison among records to identify the variations. The dataset aims to apply visual analytics to scrutinize what can be comprehended by visualizing the BIM activities contained in the logs.

Data collected from the practice would not fit this purpose because it is unlikely that the same project would be modeled more than once. Modeling hands-on in educational programs is usually divided into multiple rounds, and thus it may cause inconsistency among participants in timelines. We planned the modeling workshop to collect conditioned log files for these reasons [202].

The workshop was held over two days, as shown in Figure 14. Undergraduate and graduate students not familiarized with Revit were targeted. Before the workshop, consent to use the work and the research results were solicited. Seven students expressed interest in participating.

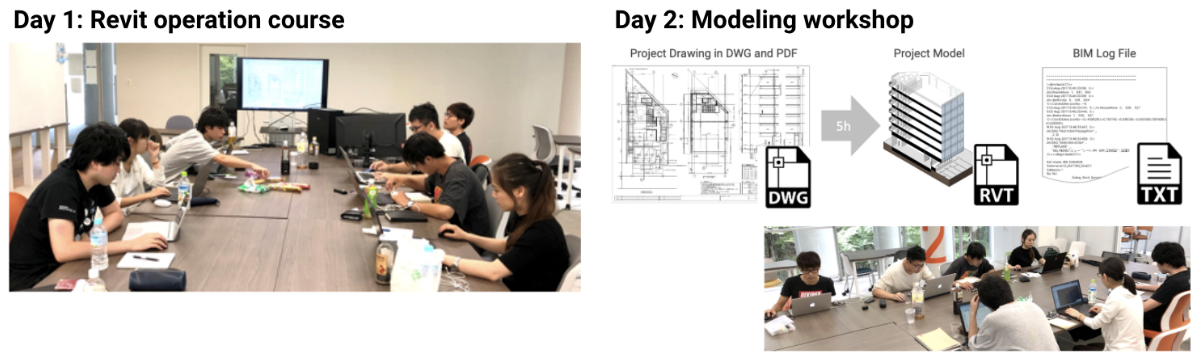

Figure 14. Scenes from the modeling workshop.

The first day was August 17, 2018, with a tutorial on the basic operation of Revit. The session was hands-on, and questions on uncertain points were resolved therein. The contents and the session record are available online [203].

As a modeling exercise, we had participants complete a building design by modeling from scratch on the second day. The author prepared the specimen seven-story commercial project, which has 2,000 square meters of floor area in total. The floor plans from the second through seventh floors are identically designed as typical floors. The design includes the facade, partition walls, staircases, openings, and bathroom, but not the furnishings. An editable CAD file was available for participants to trace the imported native file. The author responded to questions about the operation and the interpretation of provided information. Figure 15 shows the sample project drawings.

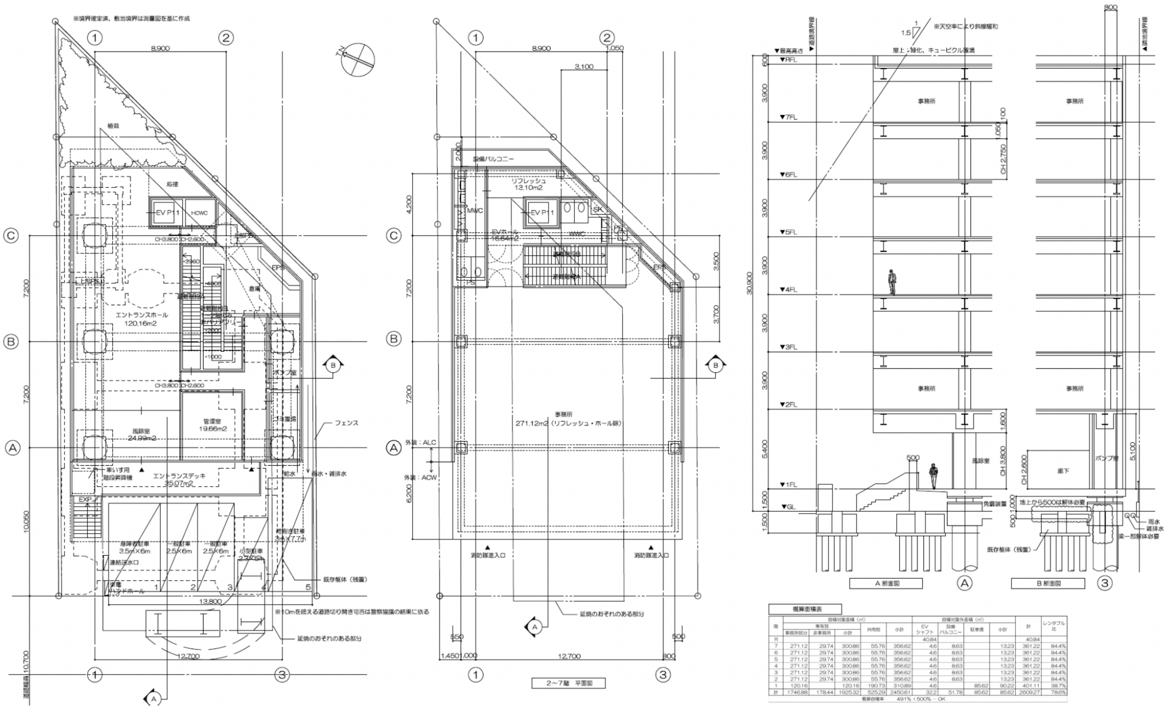

Figure 15. Input CAD drawing of the sample project for the modeling workshop.

All participants attended the workshop in one space, using Revit pre-installed laptops. The workshop started at noon on August 24, 2018, and ended at 5:00 p.m. Rest breaks were allowed as needed but were included in the workshop time. The model and log files were submitted right after the program to the author.

Table 6. Details of dataset 1: demographic information and key statistics of collected logs.

Label	Affiliation	# of issued commands	# of issued command types	Level of experience
A	2nd year at the graduate school	651	56	New to Revit
B	2nd year at the graduate school	684	58	New to Revit
C	2nd year at the graduate school	662	65	New to Revit
D	1st year at the graduate school	1,403	84	Revit experienced
E	2nd year at the graduate school	669	61	New to Revit
F	2nd year at the graduate school	635	63	New to Revit
G	3rd year, undergraduate	1,286	84	New to Revit

Dataset 2

Dataset 2 was collected from thirty-seven data donors belonging to ten organizations. Each data donor manually sent the log files via email or file transfer services from February to May 2018. Overall, 1,299 files were collected, which contained 622,793 commands. Past studies have probed between 181,969 to 620,492 commands, and thus a dataset of this size was targeted to draw parallels to the existing literature [104], [105], [122]. Table 7 describes the details of the submitted log files, the donors, and the organizations involved. Besides architecture firms and general contractors, the donor organizations included a university, a BIM operator firm, and BIM consultants. The general contractors labeled A, H, J is the international branch offices of F. All firms provide design-build service, including the engineering of structure, MEP and construction. Though their BIM workflows generally follow the same principle, the details are individually interpreted, reflecting the local collaboration schema. BIM operator company E exclusively serves F to outsource the CAD and BIM workforce. The BIM consultants provide a similar service. Company G additionally provides the strategic planning for BIM implementation and advancement. The data donors from organization D were the students taking an architectural modeling course. The project BIM models were not collected for confidentiality reasons.

Table 7. Details of dataset 2: organizations and data donors.

Label	Type of organization	Country	# of data donors	Data donor's role	# of log files
A	General Contractor	China	2	To audit received design models for construction study	37
B	Architect Firm	France	1	To audit and amend multiple design models by other in-house BIM staff	12
C	BIM Consultant	Japan	1	To coordinate received design models	73
D	University	Japan	3	To create models for design studio	46
E	BIM Operator Firm	Japan	10	To create and amend design models as per instruction by organization F	272
F	General Contractor	Japan	4	To create, coordinate and issue design and construction model	110
G	BIM Consultant	Singapore	8	To support the BIM process	264
H	General Contractor	Singapore	5	To develop construction models from received CAD design drawings	355
I	Architect Firm	Singapore	1	To create design models for projects	11
J	General Contractor	Slovakia	2	To create design models based on CAD drawings by in-house architects	119
Total			37		1,299

Dataset 3

A major Japanese general contractor and its subsidiary company have supplied the BIM log data for dataset 3. This company is one of the largest general contractors in Japan that handles many design-build projects. The affiliated employees are Permanent staff as lifetime employees hired right after graduation and External staff as short-term temporary employees.

The data was collected from Permanent and External staff working at the Tokyo office of the firm above and employees engaged in BIM-related work at its subsidiary company that provides drafting services. In traditional Japanese companies, the hiring, employment, and evaluation systems differ greatly between Permanent and External staff. To date, functions like CAD operators have been mainly outsourced to External personnel. This tendency also applies to BIM. Therefore, we differentiated between the two by using the attribute "affiliation" to indicate the type of staff (Permanent or External personnel).

The data was collected in the manner described below. We extracted employees who had used Revit from the software activity records accumulated by each company. Only those who agreed to the data collection method and purpose of use were eligible for the data collection. To minimize the burden of data transmission and prevent missing data, we installed a batch program for data transmission remotely and automatically acquired the log files. The program automatically stopped after the scheduled data capture period. From 238 targeted users, 182 persons had provided the data. The rest either declined to cooperate or failed to transmit their logs due to telecommunication problems. The number of people aggregated by affiliation and department is shown in Table 8.

Table 8. Details of dataset 3: Number of data donors per department and affiliation.

		Permanent staff	External staff
Design department	Architectural design	14	17
	Structure engineering	15	7
	MEP engineering	8	2
	Other (computational design, BIM promotion)	9	2
Construction department	Production detail design	11	9
	Quantity survey	1	0
	Construction	14	27
	Construction, MEP	8	0
Administration		4	4
(Subsidiary company)		0	30
Total		84	98

Creating Databases

The classification aimed to separate the log files based on the types of and frequency issued commands during a single software session. The clustering process requires the structured aggregation of the issued command types per user. The authors tailored Python scripts to parse the unstructured text in the collected log files. The results were accumulated in a Comma Separated Value (CSV) format for the subsequent analysis.

First, the Python code reads lines from a series of log files to extract the unique IDs of issued commands triggered by the tag "Jrn.Command". The extracted IDs were added into a single CSV file as a command sequence per log. Dataset 1 also includes the relevant timestamps for each command to visualize operational sequences precisely. Figure 16 shows the log content and the cleaned CSV of commands and timestamps.

Figure 16. The content of the collected log and the cleaned command sequence.

Second, the invalid command "ID_CANCEL_EDITOR" was omitted from the sequence. Every time the user presses the escape key, this specific command is issued to cancel their current command mode. This action follows the treatment in the preceding studies [104]–[106].

Third, the CSV files per log are further aggregated into one table. Each line represents a log with the summed counts per command within a software session. Logs are named to distinguish the users and organizations. The clustering algorithm runs on this dataset to partition the logs according to their commonalities in command counts. The algorithm up to this process is outlined in Table 9.

Table 9. Algorithm for data collection and cleansing.

```
Algorithm 1: The data cleansing and summation
Input: log files j embedding username Un and sequential number Jn
Output: output table in csv format t, df

FOR all files in j
    FOR all lines in j(Un, Jn) Do
        IF "Jrn.Command" is in line THEN
            extract Command_ID, Command_Timestamp from line
            write CommandID, Command_Timestamp into t(Un, Jn)
        ENDIF
    ENDFOR
ENDFOR
FOR all files in t
    FOR all lines in t(Un, Jn)
        Count commands per type
        Write username, counts(command_type) into df
    ENDFOR
ENDFOR
```

Clustering Algorithm

The comparison on table 10 shows the silhouette coefficient values for the result of partitioning Dataset 2 into 30 clusters, testing for each of KMeans and VBGMM with and without tf-idf application. Since the maximum value among the combinations represents the most successful separation, VBGMM without Tf-idf was selected as the best estimator. This choice is consistent with the K-means method that implicitly assumes hyperspherical clusters in shape and numbers of objects in clusters are equal, so it is challenging to extract structures that violate this assumption. The following sections show that the cluster sizes are broadly diverse, reflecting distinct characteristics.

Table 10. Silhouette analysis for algorithm selection.

	K-means	VBGMM
Tf-idf applied	0.191	-0.059
Tf-idf not applied	0.146	0.308

Although the algorithm requires determining the number of clusters to partition, this value is non-deterministic. As an exploration, the silhouette coefficient is applied to experiment with the different numbers of clusters, whose list is shown in Table 11. Considering that the randomness of the initial values affects the clustering results, no prominent tendency was observed. Too few clusters seemed not to yield the desirably discriminating results for a broad range of data sources. Therefore, we hypothetically employed 30 clusters and attempted to interpret the results through visual analytics by incorporating the user survey. The clustering algorithm jointly executed with the earlier procedure is expressed in Table 12.

Table 11. Silhouette analysis for determining the number of clusters.

# of clusters	Silhouette coefficient
15	0.306
20	0.316
25	0.309
30	0.322
35	0.34
40	0.322

Table 12. Algorithm for data collection and cleansing.

```
Algorithm 2: Clustering by VBGMM
Input: CSV file df, Cluster number k empirically determined by Silhouette Coefficient
Output: Expected label in VBGM El

Convert df into matrix
Initialize parameters k
Perform BayesianGaussiannMixture on df
Get El for each prediction in matrix
Append El for each line in aggregation.csv
```

Supplemental Data

Dataset 2

The authors additionally carried out a user survey about the data donors in August 2018 to acquire the donors' BIM skills and project status. Twenty-six out of the thirty-seven data donors answered twenty questions, detailed in Appendix A. Since the interpretation of the analysis result hugely depends on the actuality, commonly as the ground truth, we must have some statistical facts that the findings can be examined against. This selective questionnaire was designed to investigate the data donors' career background, the perceived intensity of BIM use, the nominal status of the project BIM model, especially in relationship with the drawing approval, and their attitude towards BIM-based workflow. This result was combined with the BIM log database.

Dataset 3

Large-scale BIM project collaborations usually require the combined use of software besides Revit. For example, Archicad is used in Japan to a similar extent as Revit. Rebro, a software product developed in Japan, is extensively used for mechanical and electrical design. Also, managers usually prefer to use integrated software such as Solibri and Navisworks as viewers.

These are aspects impossible to decipher from the Revit logs alone. These applications do not provide as abundant records of the process as Revit does. Therefore, we sought to grasp the intensity of software usage by counting the software running time per user.

For the above users, the session times of the representative BIM-related applications were aggregated for joint analysis with BIM log. The software included BIM modeling software (Revit, Archicad, Rebro), authoring software (Solibri and Navisworks), and drafting software (AutoCAD). The running duration of those applications is automatically recorded separately from the log collection process. The time summations per user from 1 January 2019 to 28 February 2019 are adopted for the analysis. The accumulated time may indicate longer than the actual working time because the different versions of each software may have been run simultaneously by an identical user.

Ethical Consideration

All physical, social, psychological, and other negative effects on data providers must be minimized. Based on the most important principles presented by Bryman and Bell [204], the following issues are carefully considered in conducting the research process.

Voluntary participation: The data donors have provided their data voluntarily and have not been coerced by the author or any third party. The data donors can withdraw from the participation at any stage when they wish to do so.

Informed consent: The data donors have provided their data after consenting to the purpose and expected contribution of the study. The author has informed the data donors about the types of information recorded in journals. It was declared that no forms or sources of funding were affiliated.

Appropriate communication: The use of offensive, discriminatory, or any other unacceptable language was avoided in the questionnaire and interview sessions.

Privacy and anonymity: The security of participants is of the highest importance. The data will be controlled by labels and not represent a specific individual. No information that could identify the data donor will be disclosed.

Acknowledgement of work: All works of other authors used in the research are cited along with the referencing system.

Objectivity. All data donors have been informed in advance that their submitting data will be used for this research purpose. The data was used strictly for the research purpose only. The results of this study will be prevented from being linked to other results by any third party.

Summary

In this chapter, we have obtained three datasets from respective ranges of participants for further exploration. The datasets consist of the cluster label partitioned by the unsupervised machine-learning algorithm. The estimator was evaluated by the validation factor named silhouette coefficient. The appropriateness of set numbers of clusters is examined in the empirical chapters since those are not predetermined due to the algorithm's nature. As the security of the data and donors are of the utmost importance, ethical consideration was made, as explained in the separated section.

Chapter 7: Empirical study 1

Overview

Steady modeling progress and design option exploration are vital in the early design stages. As the project comes to the construction phase, numerous amendments and revisions are required besides the model creation. The proportion of drawings generally increases as projects progress.

The interpretation of recorded BIM activity facilitates reviewing the dynamic changing collaboration formation. For example, creating walls is one of the typical commands in modeling software. The frequency and context of this command imply the situation of BIM use. However, a full-scale analysis will feed overwhelming information, thus not useful in practice.

Due to strictly classified BIM components, similar operations are often undertaken by different individual commands associated with the object category. For example, Autodesk Revit has tens of different commands that can be used to erect walls in the model. There exist four different commands to create a straight wall depending on whether it is a structural wall or not and refers to the existing linear geometry. To paste objects from the clipboard, a user has six choices of commands per the object alignment. It is known that the general commands are most frequently used compared to the function-specific commands [205]. Preceding research has mainly focused on the most frequently used commands collected from BIM logs; however, less frequently used commands may need additional attention if they have significance to the project. Such less frequent yet relevant data entry, known as weaker signals in the data mining field, requires specific processes to be equally treated with the very frequently issued commands.

As the first step of the empirical studies, visual analytics is applied to closely look at the collected logs from the normalized input condition. The patterns of modeling progress are displayed as the issued command plot along the sequential timeline. The differences observed and the need for reducing dimensions are discussed.

Data Exploration

The collected log files contain the record of the modeling process for the sample project. While the modeling commands could directly run on the imported drawing data, a certain reading level was necessary to fulfill the information required to complete the model. Naturally, the submitted model showed a minor variety caused by the digestion and interpretation of the provided information. The differences were observed in the areas, including the balustrade, door height, or mullion layout in exterior curtain walls. The non-exhaustive model views from the submitted models are compared in Figure 17. Nonetheless, all the submitted projects accomplished the baseline of required modeling quality, with columns, walls and floors at the designated levels.

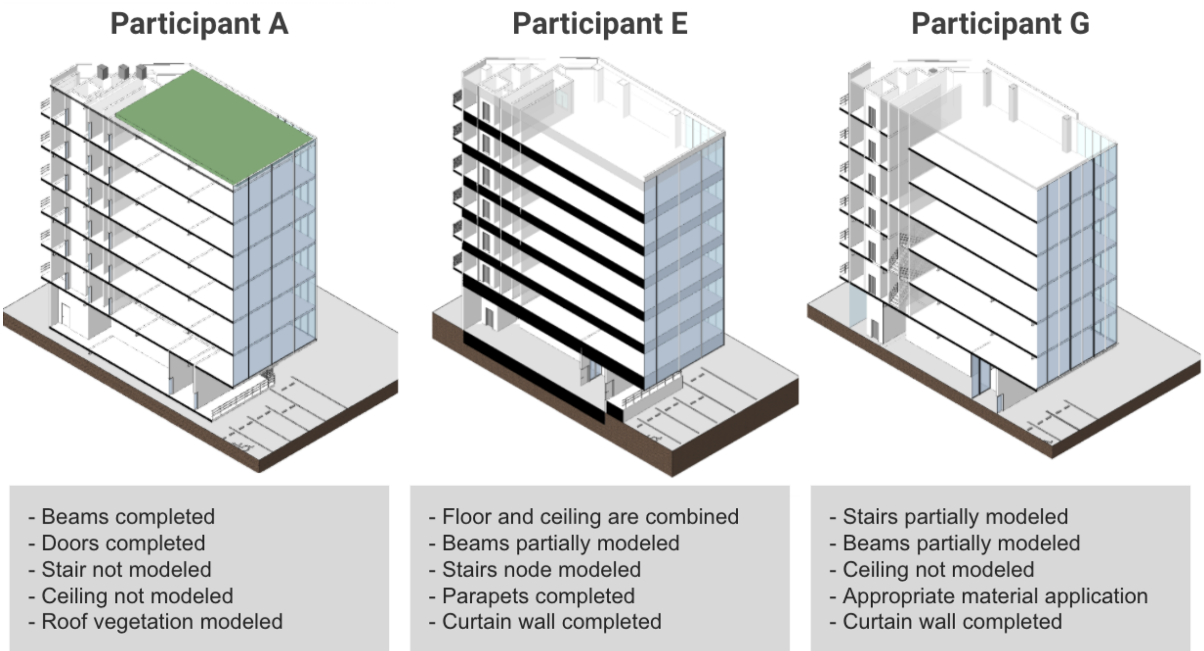

Figure 17. Submitted models in 3D view and highlights of model completeness.

Some statistical factors of the aggregated issued commands from the submitted log files are presented herein. In total, 179 types of commands were issued throughout the session. The count of issued commands per type, presented in Figure 18, shows a long tail distribution. Whereas the top-three commands (excluding ID_CANCEL_EDITOR) are all issued more than 300 times, most commands appear only a few times in the whole session.

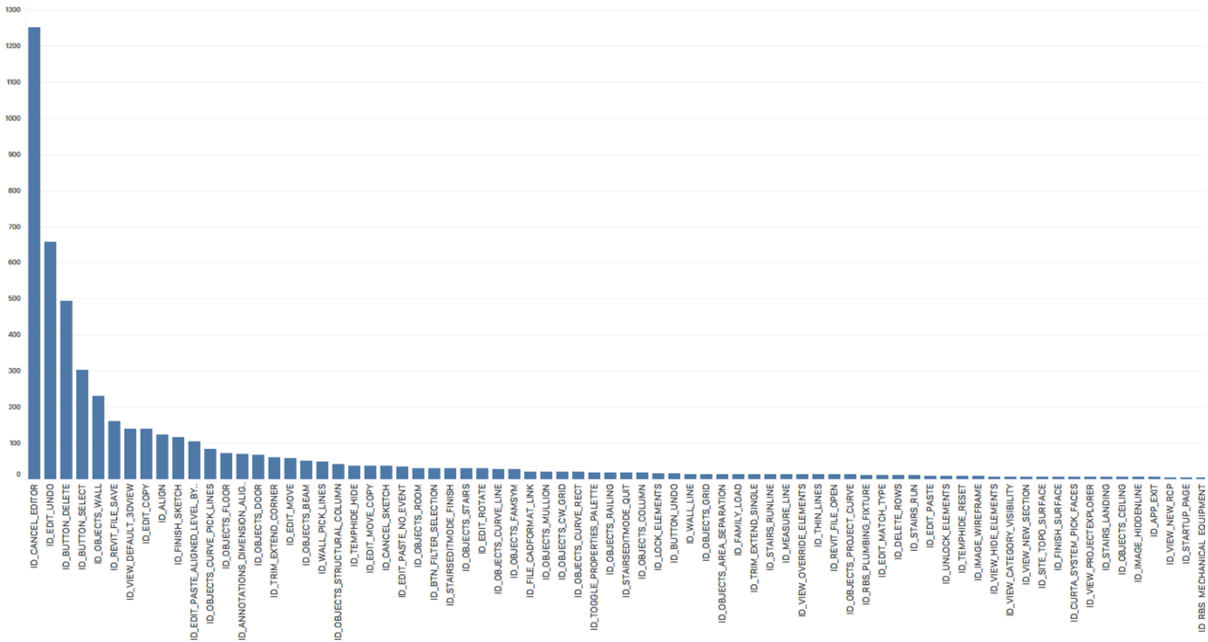

Figure 18. Distribution of frequent design commands, all users.

The plot in Figure 19 represents another visualization of the collected log. All records of commands accompany its timestamp of issuance. The plot of issued commands per type along the modeling timeline is the direct visual expression of the modeling progress. Obvious patterns are observed in some commands, for example, ID_OBJECTS_WALL (to erect wall object), ID_OBJECTS_FLOOR (to create floor object), and ID_EDIT_PASTE_ALIGNED_LEVEL_BY_NAME (to paste the copied objects from one level to another). Comparing the patterns among the participants is useful to identify the traits of the modeling approach. However, it requires the categorization process because the dimension of the plot is overwhelming for cross-comparison purposes.

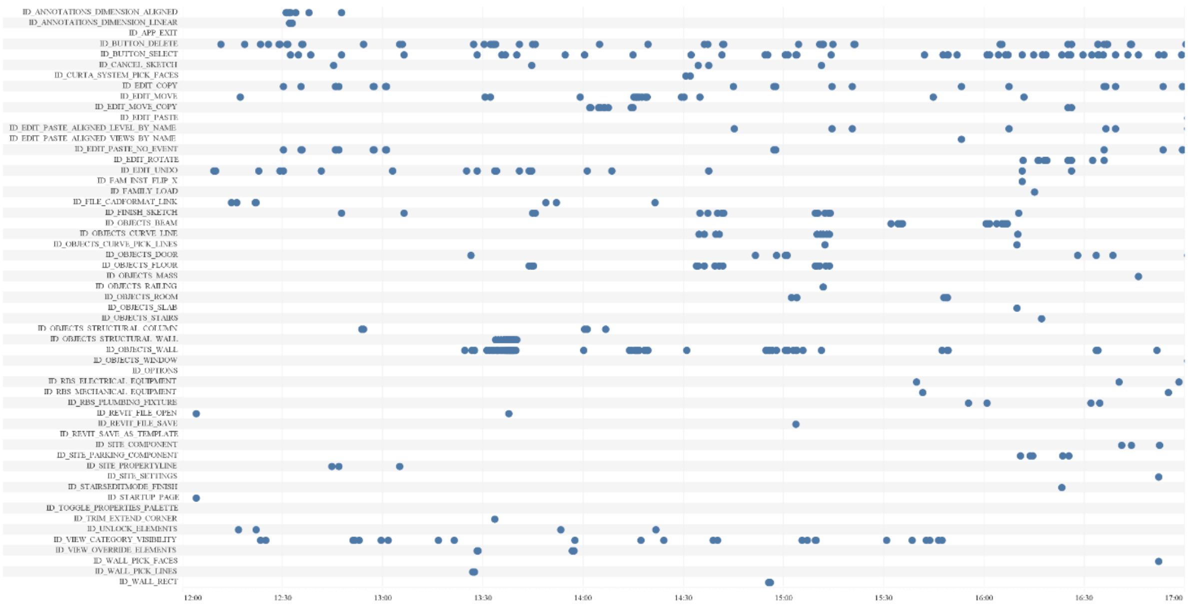

Figure 19. Visualized modeling sequence for user A.

Grouping of the command types into a few categories aids in excavating the hidden pattern. Considering the main activities for model creation, eight categories are formed for all commands used in the workshop to be classified. Namely, annotation group for adding texts and dimensions; edit group for cut, copy or paste of elements; family group for loading and placing reusable model components; file group to open or save a file; object group for adding new model elements like wall or column; view group to extract 2D or 3D view for documentation. The rest commands are all categorized under the miscellaneous, which are insightful to visualize the activeness of users. The counts of commands aggregated per the above categories are tabulated in Table 13. Effective in total command counts that exclude the invalid command (ID_CANCEL_EDITOR) represents the mean contribution to the project progress.

Two users, D and G, displayed remarkably high counts in total issued commands, largely associated with the high intensity shown in the object group. It explicitly offers that these two participants were more successful in steadily creating models than others. Although the rest of the users executed a roughly similar amount of commands individually, their composition varies from one to another.

Table 13. The aggregated counts of issued commands in collected BIM logs per user.

User	Total command counts			Counts per command category							
	Issued	Effective	By Type	Annotation	Edit	Family	File	Objects	View	Invalid	Miscellaneous
A	651	600	56	12	126	3	10	177	29	51	243
B	684	611	58	1	258	2	10	105	76	73	159
C	662	653	65	3	182	4	93	106	29	9	236
D	1,403	765	84	46	185	2	37	141	8	638	346
E	669	619	61	2	154	2	6	97	3	50	355
F	635	431	63	4	87	6	7	102	12	204	213
G	1,286	1,005	84	15	239	6	25	280	69	281	371

Visual Analysis of Modeling Approaches

It was noteworthy that the compositions of issued commands were diverse among the participants. The model deliverables did not display a large difference; thus, the individual modeling approaches caused the variety. The timeline plot provides a closer look for this aspect per categorized modeling commands.

The simplified visualization for all participants is exhibited in Figure 20. Commands to make new components belong to respective categories from number one to eight. Additionally, the commands related to model copy and paste, which also contribute to model making by the duplication, are combined into one group at number nine. The rest commands are all categorized in number ten as others except for the invalid command.

Some users did not execute specific modeling commands. User A, B, C, and D did not address the ceiling modeling during the session. User C represented the ceiling with the next floor, while the rest models did not represent the ceiling. Similarly, some realized that the beams are necessary, which only appear in the section drawing.

In principle, it is reasonable to start modeling from either wall or column, as the structural key elements in plan view, followed by the floors. The opening, beam or plumbing do not appear earlier because they need other geometry to host the placement; doors, for example, cannot exist in models without being hosted by a wall.

The prominent difference is observed in the commencement of model making. Users D, E, and G started creating walls immediately, while others spent 40 to 50 minutes before effective action. In any case, a short span sequence of command repeats appears once they start creating one category of the element. This tendency implies that the participants settle the modeling strategy that navigates what to create next.

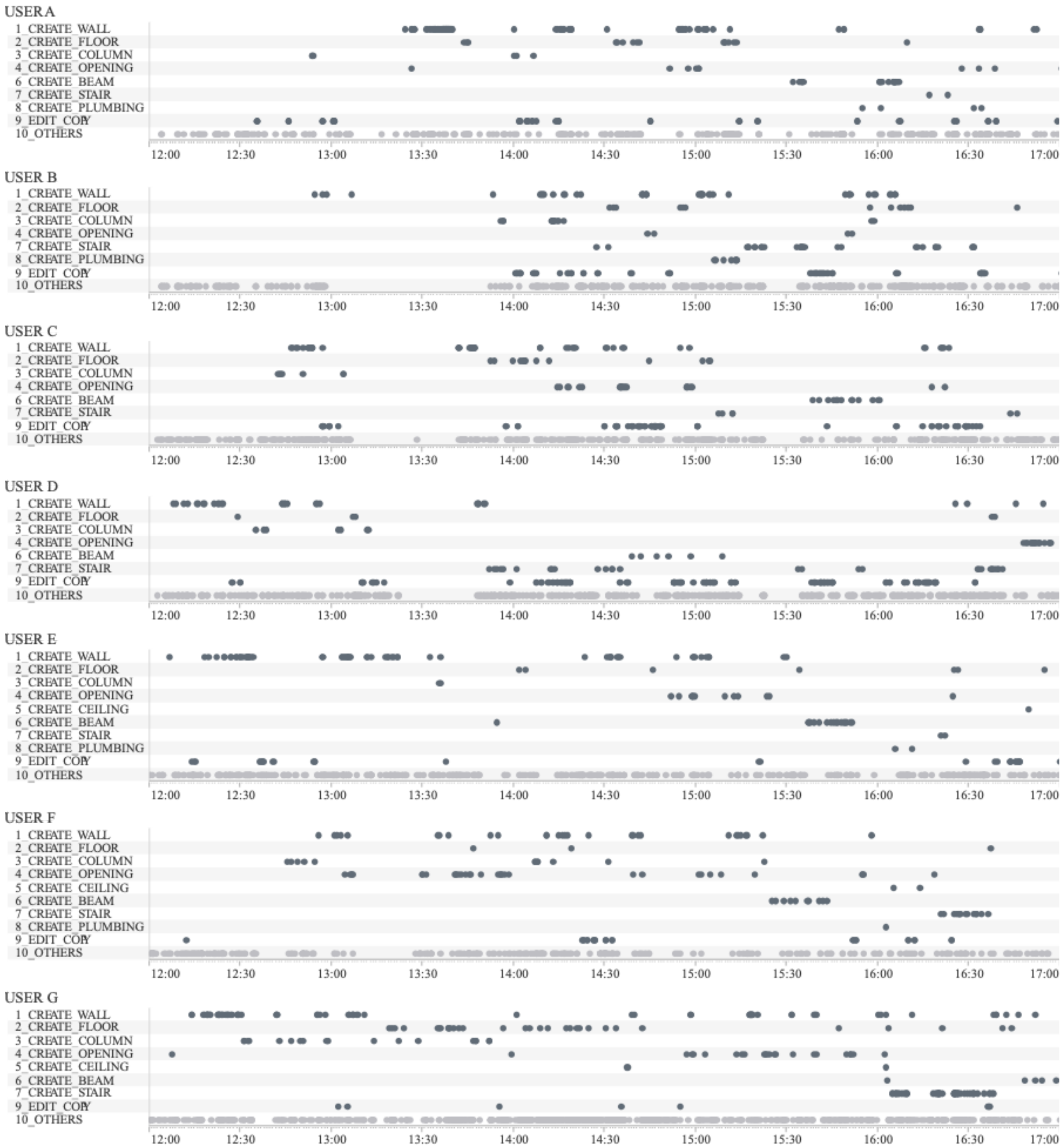

Figure 20. Visualized modeling sequence per participant, grouped by command category

Visual Analysis of Modeling Progress

The short, frequent intervals in 10_OTHERS can be found in sequences: it shows their halts in modeling operation. The modeling commands are also fewer in such blank time. Also, there are certain periods when no modeling category is selected, whereas the other commands are in motion. Such phenomenon is observed in all users, typically in User A, C, and E. The sequences conversely illustrate their halts and breaks in operation are shown in Figure 21.

All users successfully imported the project CAD file into Revit. It was essential to standardize the output and offer the elements to be created next by allowing users to trace every element displayed in the provided drawing. However, every user had halts when no modeling operation happened. It was a tendency that the users who started erecting walls and columns earlier experienced less frequent halts than others.

There are two potential reasons for these suspensions in modeling operations. One is that a user had a technical problem proceed. Some users may immediately ask the tutor to resolve the issue. However, a longer suspension will occur when users attempt to solve trial-and-error. It can be a chief reason for the blank in modeling categories.

The other reason is that a user is yet to decide the element to model. BIM software requires users to select the modeling command which is precisely relevant to the element category. Unlike the 3D modeling software, BIM software does not create the generic geometry and set its category afterward. Therefore, the elements expressed in drawings need to be explicitly ordered by the modelers to have no hesitation in choosing the right command. The users who chose the wall command earlier had fewer intervals and eventually used the modeling strategy successfully by breaking down the modeling steps.

Figure 21. The visualized non-operating period in modeling sequences per participant

Summary

Various formations are possible to supply the BIM workforce with a project. A group of BIM-enabled specialists may fluently converse over models; analyzing the frequency of model use should enhance BIM communication. The intensiveness of model-making especially matters when specialized personnel like BIM operators undertake BIM tasks; in this case, engagement of other project members is vital to leverage the building information for projects.

The relationship between diverse organizations and the functionality BIM software provides dynamically transforms depending on the collaboration structure or project requirement. Stakeholders increase in large projects, and thus the need arises to mediate more complex connections.

Chapter 8: Empirical study 2

Overview

This chapter practices visual analytics by dramatically expanding the target of the BIM logs treated. The subject journal files are collected from a variety of Revit practitioners. Unlike the data in the previous chapter, there is no uniformity in the associations, discipline, level of experience with BIM, type and phase of the project among the participants. Once the developed methodology allows for use under these conditions, it will be a highly versatile technique applicable to diverse collaboration schemes.

The variety of commands overwhelms the scope of understanding at a glance. There exist multiple plausible options for modeling the identical input, and the possible working steps are countless. The clustering estimator provides an efficient mechanism to categorize these factors into a few groups for visual analysis to interpret these factors in a semantically coherent manner. The algorithm selection method is described in Chapter 7.

Dataset 2, analyzed for use in this chapter, comprises BIM logs collected from ten organizations, including design firms, general contractors, consultants, and universities. The expertise, activities, and work protocols of the participants differ significantly. Because this fact matters in the verification phase, the authors conducted a questionnaire for the participants to validate the usefulness of the proposed method by comparing it with the results of visual analysis.

The method devised in this chapter directly augments the existing BIM log mining. Existing techniques are predominantly job-specific and therefore do not assume a multi-disciplinary environment. Inevitably, the details and procedures of the BIM activities can be approximately estimated. This method abolishes such assumptions and demonstrates the possibility of capturing the whole picture by following a classification procedure, even when the details of activities are unknown. Appropriate data projection enables bias-free comprehension of BIM activities recorded in the software outputs.

Interpretation of Obtained Clusters

Figure 22 summarizes the clustering result for Dataset 2. Two different indices are expected to measure the cluster size: the cluster size and the average number of executed commands in those logs. Clusters with a high number of log files indicate that they are observed more frequently, and the average number of commands is relevant to the users' activeness, thus approximately indicating the level of contribution to the model.

The separation results, viewed from the number of log files in clusters, are distributed long tail. On the other hand, clusters #7, #25, #1, #20, and #27 stand out in terms of the average number of events, while the rest have less than a few dozen records overall. Tens of commands are practically very few for substantive modeling contributions to project BIM, like creating architectural elements and drawing annotations. Therefore, a log with a small number of average command execution implies low engagement of users with model progression but rather in terms of, for example, checking content and interacting with other environments.

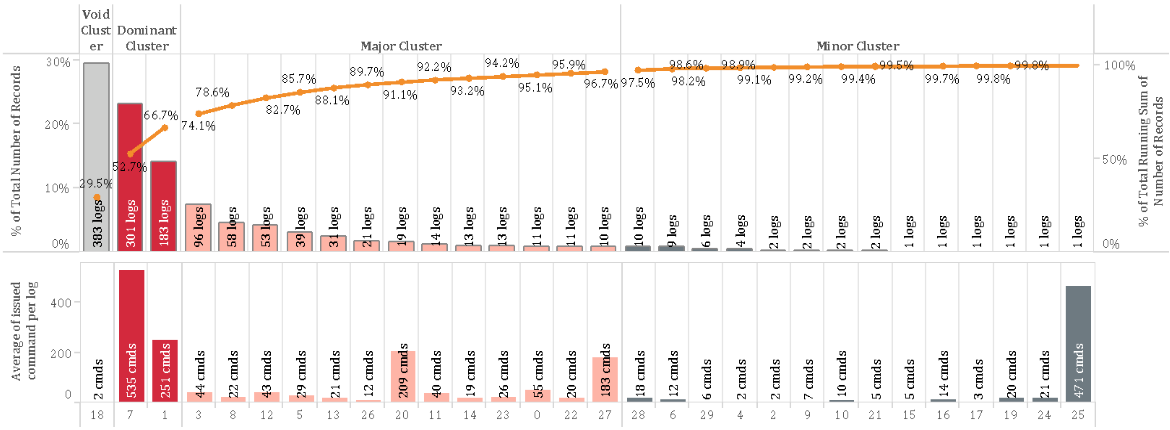

Figure 22. Overview of predicted clusters with four cluster types, dataset 2

The distribution of logs and executed commands offers four major tendencies to which the obtained clusters can be further grouped. The first is the Void cluster; the very distinctive cluster #18 forms a group by itself. Whereas it accounted for 29.5%, the largest clusters obtained, it contained only two events on average. These extremely few operations imply that a user opens the model file and exits the software with almost no action. Possible situations include opening the wrong file, checking the model version, or quitting it without knowing what to do.

The second is Dominant clusters that account for 66.7%, including Void clusters. The logs under this group have characteristically high average numbers of recorded events. This type frequently appears, indicating that a user performed intensive operations during the software session. It is reasonable to assume that this log signifies the main contribution to creating and editing the model.

Finally, close numbers of clusters belong to groups when the remainder is split at the double standard deviation in the running total, respectively termed as Major and Minor clusters. Both cases do not present high occurrence, and the average command issuances are also not as massive as in the Dominant cluster.

Several visual analysis approaches interpret the clusters and their groupings a the subsequent sections.

Command-Based Analysis

The functionality of issued commands per log and cluster plays a vital role in comprehending the result of an unsupervised machine learning algorithm. The 798 different commands contained in records can be categorized into seven by their purpose: i) modeling commands (to generate components), ii) drawing commands (to draw or annotate in two-dimensional), iii) editing commands (to edit existing elements), iv) save commands (to save or synchronize current file), v) imp/exp commands (to import, export, link and manage relevant files), vi) workset configuration (to set or activate workset) and others as vii) miscellaneous. Figure 23 illustrates the ratio of each command function category per cluster.

Progressing modeling is an elementary contribution to BIM throughout the entire project lifecycle. The dominant cluster has the highest proportion of modeling commands, and many clusters in the major cluster also display a high ratio, most notably cluster #20 as the extreme. Adversely, the clusters under Minor and Void cluster groups do not have such a feature. Drawings are still paramount in most BIM workflows. Interestingly, drawing commands are prevalent in minor clusters, particularly clusters #6, #10, and #16. Imp/exp commands and workset configuration are typically used in integrating multidisciplinary models or site models; thus, single-model projects seldom use this functionality. Therefore, log files characterized by these commands exhibit the active collaboration occurring in the BIM environment. These commands scarcely appear in Dominant clusters and are more common in Major and Minor clusters. It implies that the users are more responsible for collaboration than modeling, such as checking, coordinating, and outputting.

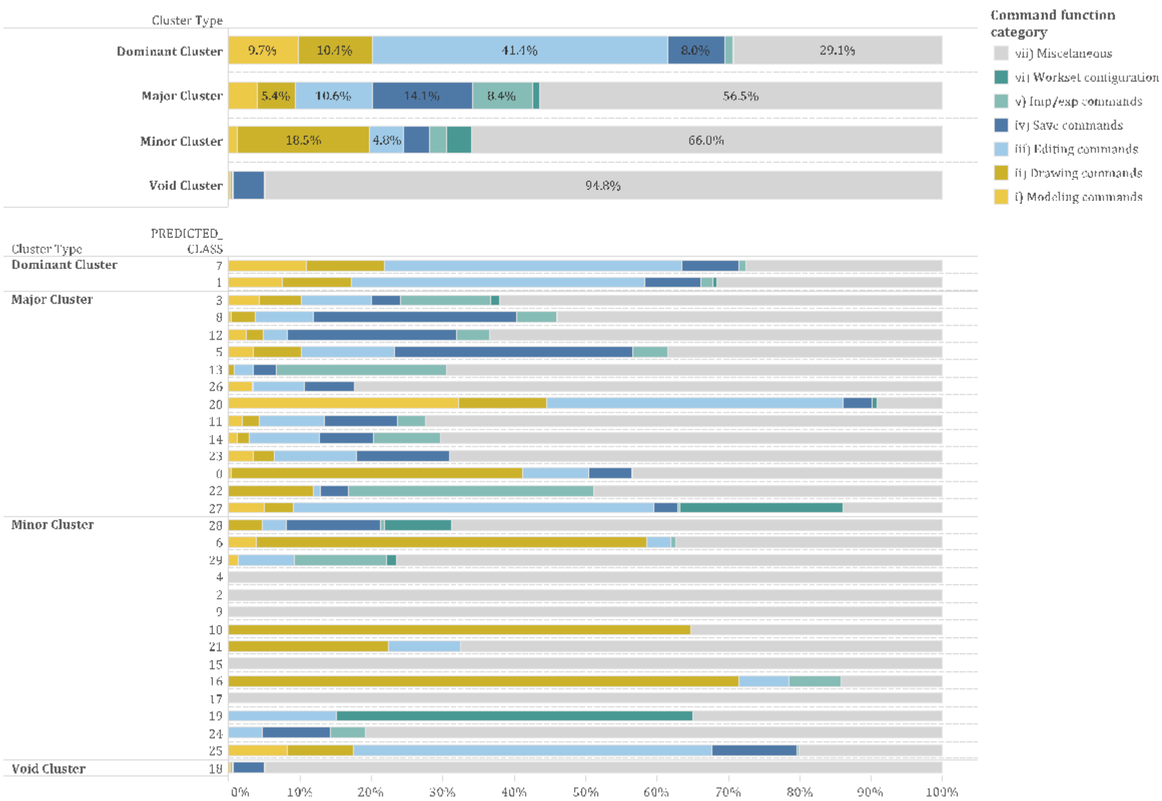

Figure 23. Command-based visualization of predicted clusters.

Whereas the proportion of command categories depicts the clusters under dominant and major cluster groups, minor clusters present distinctive distributions. For example, the miscellaneous command category occupies clusters #4, 2, 9, 15, and 17. Drill down to the individual commands will reveal the meaningful contributions. The top three most frequently-issued commands in minor clusters are listed in Table 14.

Table 14. Top 3 most issued commands per cluster in Minor Cluster Group, rank # is among overall dataset

Cluster #	Command Function	Rank	Command Function	Rank	Command Function	Rank
28	Configure partitions	106	Relinquish model ownership	120	Open Revit file	16
6	Measuring object distance	32	Switch to default 3D view	10	Open Revit file	16
29	Create new file with template	172	Quit Application	39	Configure units	191
4	Open most recently used Revit file	91	Configure model material	146		
2	Visual programming environment	268	Create new file with template	172		
9	Render image file using cloud	213	Open Revit file	16	Quit application	39
10	Configure pen setting	288	Switch line thickness in display	66	Open Revit file	16
21	Open Revit File	16	Quit application	39	Configure pen setting	288
15	Render current view, photorealistic	162	Quit application	39	Open most recently used Revit file	91
16	Hide specified object category	129	Quit application	39	Undo	7
17	Render image file using cloud	213	Open Revit file	16		
19	Activate design option	78	Minimize view	315	Delete component	1
24	Disjoint ends of structural element	203	Switch to default 3D view	10	Save current file	12
25	Orient camera to front	144	Switch to default 3D view	10	Save current file	12

The top command in cluster #6 measures the distance between objects. This command's repeated use without accompanying modeling or drawing command outlines the purposes such as CAD-based drafting or manual quantity takeoff. Cluster #2 consists only of commands to open files and a visual programming environment termed Dynamo; the direct entry to this mode exhibits the exclusive involvement in computational design scripting, including automation or optimization. Cluster #15's commands for photorealistic rendering straightforwardly mean that the presentation image was produced in Revit. The above suggests that minor clusters are not positively associated with the modeling or drawing production, but they alternatively make advanced contributions by leveraging specialized features.

Overall, four clusters are characterized differently by the issued commands recorded in each log. Their high portion of modeling commands highlights dominant clusters; thus, the log represents the typical model maker's activity. Major clusters consist of an outstanding high ratio of import/export commands and collaboration configuration commands; therefore, it is plausible to interpret the activity as the connecting hub. Although the activity in Minor clusters is diverse, one of the traits is discovered in the prominently high issuance of drawing-related commands; hence it can be largely understood as the drafter's activity. The void logs contain little commands inside; however, the software program was surely started, and a certain operation (mostly opening the recent project file) was made. We shall tentatively interpret this activity as the watcher of project BIM progress.

Organization-Based Analysis

The subsequent visual analysis at the organizational level further investigates the clusters. Figure 24 visualizes the ratio of clusters by type of organization. Architect firms and BIM operator firms have prominently high ratios of the dominant cluster relevant to their intensive modeling works. The architect firms held no minor clusters: potentially because the architect firms were in positions to initiate or issue design intent rather than coordinating with other models. Another tendency observed was that the division of Dominant clusters and Major clusters are equivalent in BIIM consultants and general contractors; it indicates a high proportion of non-modeling work. The university's logs have a noticeably large occupation of cluster #20 that successfully distinguished the command context from the practical projects.

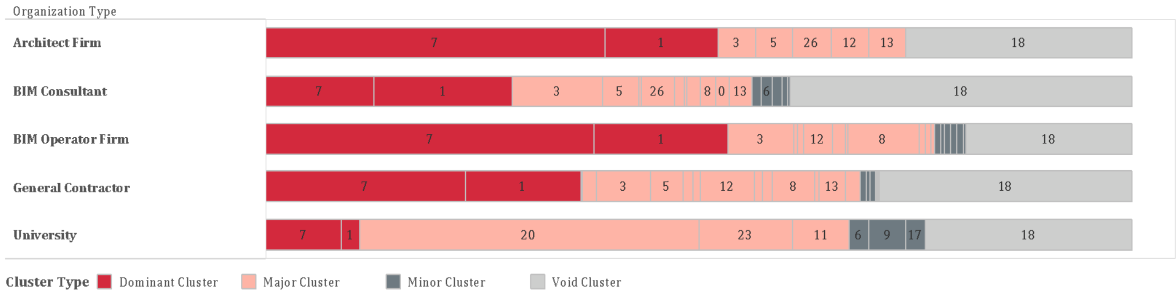

Figure 24. The ratio of clusters per type of organization.

Some organizations consisted of multiple data donors—the breakdown per data donor is separately presented in Figure 25. The size of dot plots reflects the percentage of overall logs from a donor.

The attribute of an organization often appears prominently in dominant clusters and major clusters; the log files of General Contractor A did not contain any of the dominant clusters. As confirmed in Table 15, this organization's usual BIM practice was receiving the model and applying it for construction. Cluster #6, represented by commands to measure dimensions, also reinforces that characteristic. Users exhibiting similar characteristics include user D from BIM Consultant G and user T from University D.

Clusters #20 and 23 appear almost exclusively in logs from University D. On the contrary, cluster #3, 8 contains logs for all organizations except university D, indicating that educational and industrial use of BIM was discriminated against. Investigating Cluster #27 in General Contractor A and F's logs is expected to reveal the workflow specific to these organizations.

The activities among data donors are not inevitably similar within a single organization; they are considered strategically divided. For example, in BIM operator firm E, the logs from employees E, S, and Z are primarily classified into the dominant clusters. There are also users N, O, and Y, whose records are often classified into Minor clusters. Organization E was a corporation that produced project models under General Contractor F's direction. The former BIM users concentrate on model production, while the latter audits and coordinates created models with others. On the other hand, the visualized activities of two users from General Contractor J resemble each other. The BIM tasks are evenly shared and likely managed differently from organizations E and F.

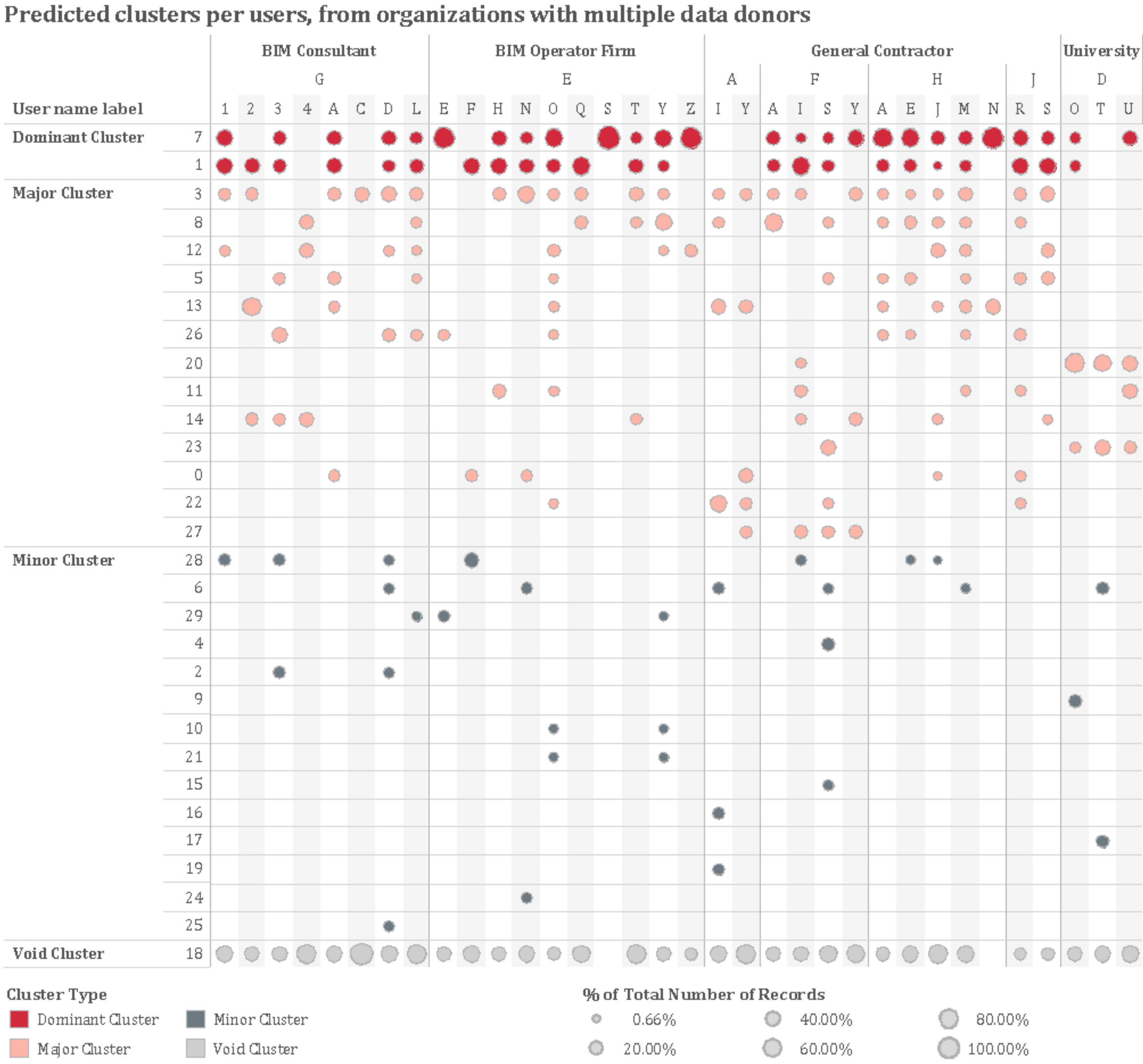

Figure 25. Clustered log file ratio per data donor under organizations.

User-Based Analysis

A series of visual analyses at the data donor level was summarized in Figure 26. Because the user survey is indispensable here to examine the discoveries, this section subjects only the correspondents to the user survey, unlike the preceding sections. The relevant questions in the questionnaire, listed in the Appendix, are indicated at the title of respective charts.

The cross-analysis with the users' discipline depicts that architect's logs are more likely clustered into dominant clusters than others. The logs from engineering (MEP) or others should comprise more non-modeling commands; their cluster distribution also confirms it.

Self-reported software skills articulate that users with proficiency left more dominant clusters and fewer void clusters. Although the proportion of dominant clusters with advanced skills was lower than the intermediate level, it becomes comparable when major clusters are joined, seemingly because of the proficient users' manifold roles in projects.

The users' year of experience was irrelevant to the clustering results. Experienced practitioners are generally apart from the BIM environment; however, this tendency was not observed since the survey participants possessed a certain level of BIM skills.

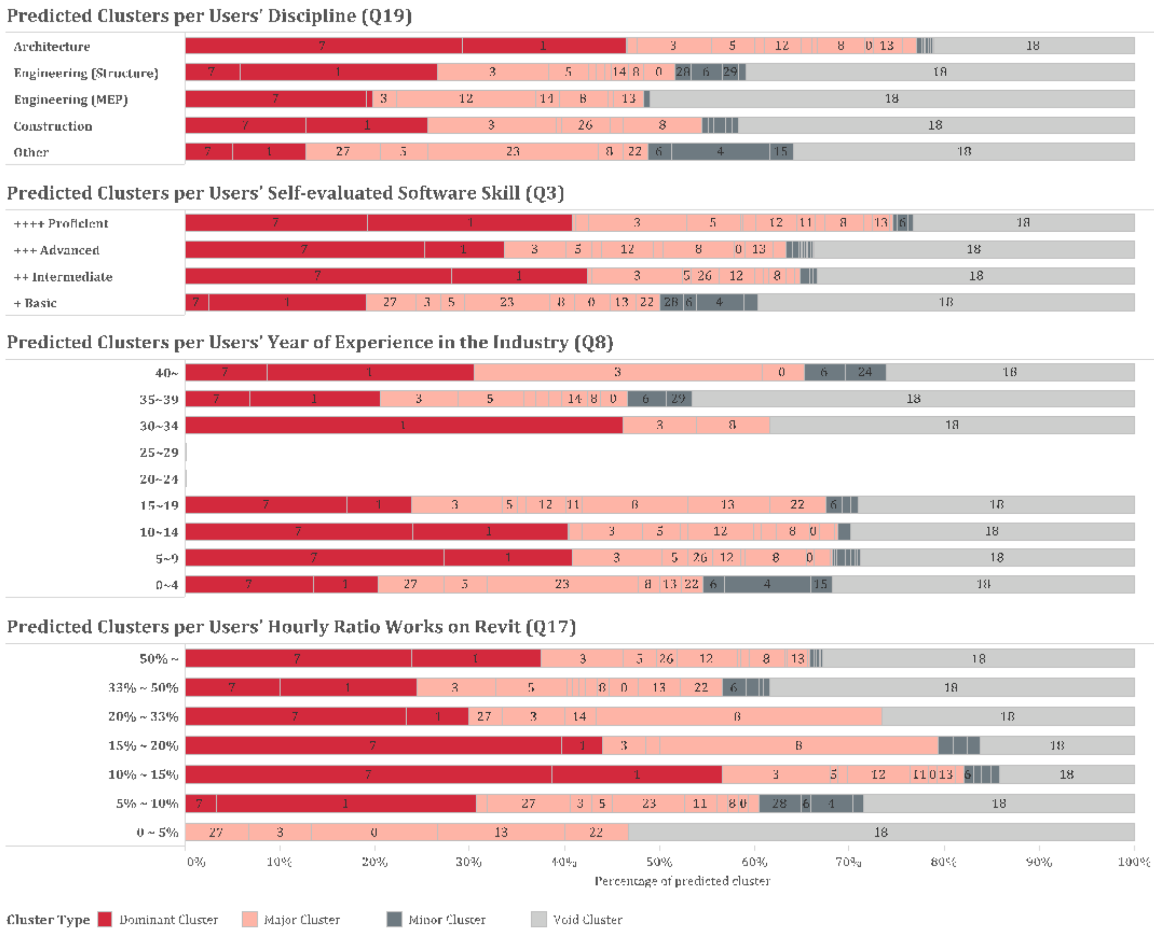

Figure 26. Cluster ratio aggregated by users per answers of questions in the questionnaire.

The software users with a lower working time presented a prominently high portion of void clusters and less or even no dominant clusters. The least amount of void clusters was found in users who spend 10-15% of their working time in Revit. Considering that more extended time in BIM software does not necessarily signify more efficient work, this observation explicitly depicts the significance of the proposed method, which can recognize the users more contributing to the project BIM progress yet not measurable by their working time or the level of self-evaluation.

Interpretation of Cluster Groups

The analyses so far enabled us to extract and interpret the clustering results. A two-dimensional plot can concisely organize the four cluster types, as shown in Figure 27, based on the number of logs classified and the model's contribution level.

The more logs categorized into the dominant cluster, the more intensive modeling work the user or group undertook. Dominant clusters become smaller when the organization is a receiver or coordinator of progressed models. The expanded non-modeling activities, particularly in minor clusters, align team performance with the desired work scope.

In BIM team collaboration, management policies hugely vary depending on the strategy. The manager may evenly split the whole BIM task and share them among members or role-specifically assign to the specialized members. The proposed system helps monitor if the worksharing is as planned and enables teams and individual practitioners to self-monitor their BIM contribution.

At the individual level, a broad range of cluster types at the individual level represents the user in charge of multidisciplinary, manifold tasks. Conversely, the same cluster repeatedly appears if the user is task-oriented. This method allows players and management to strategize to fulfill expected BIM roles and enhance their skills.

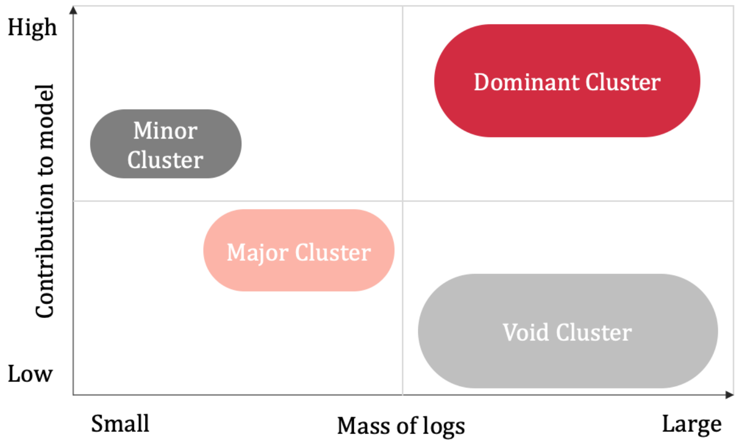

Figure 27. Abstract of cluster types from dataset 2.

Proposed Database

The most common log files were classified as void clusters in both two different datasets. As these logs possess little information, they have not been highlighted in the existing BIM log mining approaches focusing on model progress. Dataset 2 includes the data donors not deeply engaged with BIM workflow. Indeed, there were fifty-two users for whom all log files were classified into the Void cluster, accounting for 28.5% of all participants (Figure 28). While some of these users are potentially unpracticed and experiencing difficulty with the BIM, they are equally likely qualified designers who make crucial decisions by viewing the model. They may also be ingenious detailers who actively develop design by two-dimensional CAD drawings along with BIM progress. Analyses targeting only the predominant BIM users may risk disregarding those users' presence. The partitioning concept and large clustering do not filter such information; instead, they amplify those weak signals to draw enough attention to non-modeling-related activities. Hence, this holistic approach enables more inclusive analysis, especially for large-scale or multidisciplinary project orchestration.

The minor clusters consisted of commands rarely issued. Those commands often have distinguished functionality, leading to very contributing activities. Unlike modeling events that appear dozens of times, such commands are executed mostly once in the software session. The advantage of machine learning algorithms lies in capturing those offset signals and reflecting them in the classification. Thus, the application of classification strategy suits to capture the varied activities holistically and inclusively.

The case study demonstrated the idea to overview the analysis by four cluster types and their ratios at the organizational level (both by type and individual) and user level. It can likewise be applied at the group or project levels as well. This scalability also proves the significance of the proposed methodology. For example, the project BIM team's performance under a general contractor can be analyzed side-by-side against a BIM specialist company's group. The BIM collaboration in specific building types, such as healthcare or transportation facilities, can be portrayed and benchmarked with other successful past projects. Such flexibility is advantageous to comprehend the dynamic and diverse BIM collaboration landscape.

Figure 28. Distinct count of predicted class per user, dataset 2.

Interpreting visualized analysis does not demand extensive BIM software skills. It requires insight into AEC's projects and teamwork more than ever. As the management layers of projects and firms have often had limited practical BIM knowledge, the individual interview was almost the only way to investigate the real collaboration. The proposed process provides instant and detailed visualization of the BIM ecosystem. Nevertheless, this data-driven management does not exist for the sake of micromanagement. It opens the implicit process to active BIM communication for operational improvement through a dynamic, universally understandable method. Such an approach has been conventionally possible by the power of outstanding BIM managers; this study aims to democratize such tacit know-how for open and ad-hoc BIM management.

Advantage of the Proposed Process

Dataset 2 explained that the comprehension of clustered BIM logs could be enhanced when matched with information about the data donors and their organizations from three perspectives: command level, organizational level, and user level. The developed methodology has dramatically improved the readability of the visualized BIM activities. Monitoring the practitioner or firm at the organizational, project, team, and individual levels grants multiple benefits to their own, including 1) the effect assessment of BIM training program, 2) improved staffing and team building, 3) the skill design by benchmarking against others.

A project dilemma exists that the expected BIM benefit in a large project involving many stakeholders is significant, yet the project's uniqueness makes it more challenging to implement BIM. The BIM implementation in international projects tends to stall; the quality of the final output can deteriorate. Even worse, the use of BIM itself becomes abandoned amid the project.

It is pivotal that organizations and project teams identify their own organizations' traits to improve the situation. It further encourages collaboration within projects, which is the mainstay of BIM. Ultimately, the desirable lifecycle will be realized where BIM utilization will be maintained from design to construction and part of the solution for further data utilization.

While frontloading of projects is frequently referred to as the benefit of BIM, the timing of decision-making is, in practice, highly dependent on the parties involved. As previous studies have shown, rectification or amendment costs can account for more than 10% of the project cost, which is a serious detriment to the project profitability. While the impact of untimely decision-making is immense, especially for project owners, too early decision-making can drastically reduce the potential of the development and limit investment effectiveness. Therefore, it is often necessary to agree to changes that cause the rework due to the dismissed decision-making timing.

Adequate payment for such impactful changes is hardly made. As seen in the previous chapter, the change process is difficult to capture only from the final deliverables alone. Log files, however, can be used to extract any record of alteration, modification, or deletion made to existing elements. When interpreted in conjunction with the timing of the changes, it is possible to understand the magnitude of the impact that a given change has had on the design and construction process, which can serve as evidence for a corresponding claim.

The use of logs in a BIM-centered project carries a similar meaning to analyzing automatically recorded data of daily activities in an architectural project. In addition to the accumulated as-built project information, unbuilt design options (Digital Twin Prototypes, DTP) can also be included in the analysis extracted from the record, thus reaching the function of Digital Twins for not only the facility itself but the entire project space [42], [206]. From such a perspective, the non-BIM information can be integrated further for the analysis. Communication among stakeholders occurs through emails, chats, online meetings, et Cetra. Management at the construction site is controlled by individual platforms using photos, inspection records or statistics. Including even these captures, overviewing the totality of information would be considered the lifelogging for the industry. A valuable archive is created from the continuously generated records in lifelogging, expecting better management and communication [207], [208]. The inexpensiveness in information creation is extremely important there. This method contributes to increasing the value of the recorded information by swiftly obtaining understandable knowledge from the log, a byproduct of software, and bringing tangible and actionable improvement proposals.

Summary

A novel process was devised to enhance the existing BIM log mining approach. Visual analytics stands on four broad categories of BIM activities by the clustering algorithm. Case studies confirmed the method's usefulness in deciphering BIM activities at the levels of commands, organizations, and users. Intercomparison of BIM activities became possible across the organizational, project, and individual levels. The comprehensive visualization does not require BIM expertise to examine.

Chapter 9: Empirical study 3

Overview

This chapter succeeds the method developed in the previous chapter to apply to the analysis of larger amounts of records. Subject dataset three was obtained from a major Japanese general contractor. The corporation is mainly engaged in design and construction and has various departments within the enterprise. In addition to its permanent employees, the company also employs many external personnel on a short-term contract basis, and BIM-related work is being shared between them. BIM log mining appeared to be a powerful means of accurately tracking these diverse collaborative relationships. In addition, the use of software other than Revit will be included in the study, resulting in a consolidated examination with supplementary data. We stratify many users based on the characteristics of clustering log files and highlight distinctive user groups. For further drill-down, interviews with the selected participants extract the characteristic elements for successful BIM cooperation.

Clustering Result

When we developed a clustering method in a previous paper, we classified the clusters into four superordinate groups based on their similarity among each other: Void, Dominant, Major, and Minor. Though we follow that result in this paper, we also examined the number of included commands per log file belonging to each cluster for more accurate classification by project contribution. As shown at the bottom of Figure 29, there existed a significant difference in the average number of commands between Dominant and Major Clusters. It implies that the gap in contribution to the project is not negligible. From this aspect, #3, previously classified as a Major cluster, was recategorized as a dominant cluster. The updated overview of four cluster groups plotted on the size and nominal contribution to the model is illustrated in Figure 30. Hereafter, we denote the log files classified into each cluster as Void, Dominant, Major, and Minor logs.

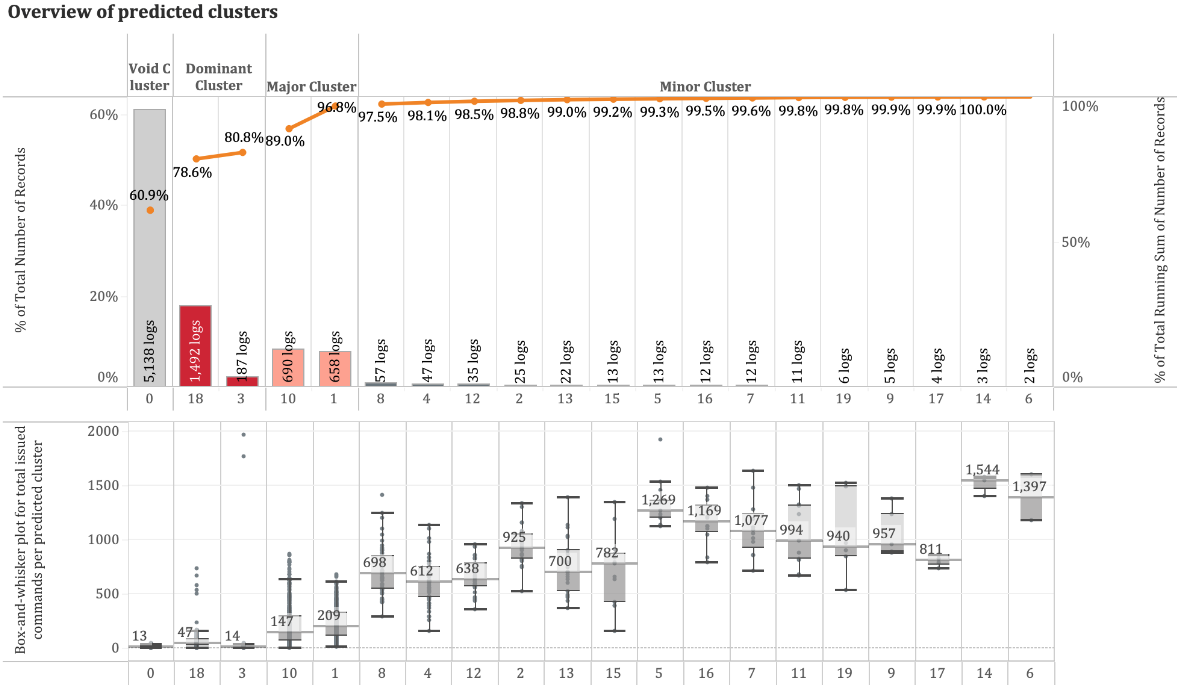

Figure 29. Overview of predicted clusters and the numbers of total issued commands per log under respective clusters, with four super-cluster types.

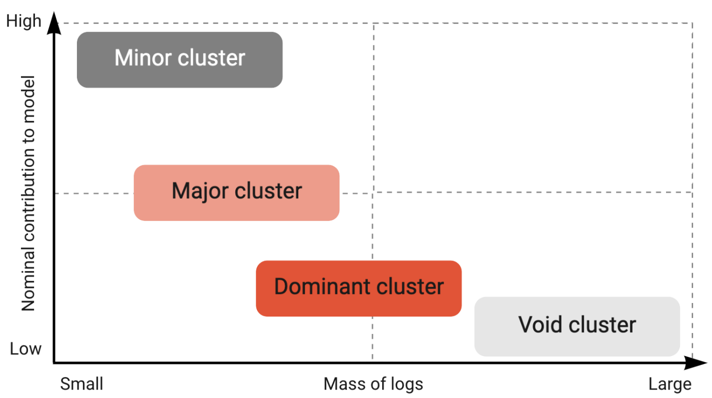

Figure 30. The implication of four cluster groups plotted on the size and nominal contribution to the model.

BIM Log Visual Analytics

Visual analytics enables us to discover patterns by projecting data on various subspaces. It is more likely to yield significant findings than methods like principal component analysis when the data comprises overwhelming dimensions compared to the data volume, as in the case of BIM logs [190].

Figure 31 shows an analysis of the number of log files collected and the number of commands executed in them by affiliation. While the number of data providers for both Permanent staff and External staff does not differ substantially, the total amount of logs collected from the External staff was 1.80 times larger than Permanent staff, and the overall count of commands issued was

3.04 times larger from External staff. The BIM workload per person is considerably higher in External personnel.

Within each affiliation, however, the BIM contributions of users are not evenly distributed. One user accounted for more than half of the number of commands executed among 84 employee users. Similarly, specific External employees undertook significantly more work. The top seven of all data contributors executed more than half of the commands issued in total.

As seen above, the degree of the project BIM contribution is not merely determined by affiliation. In Japan, cooperative relationships are generally established without being restricted by the definition of job responsibilities, and thus the reality of work in projects is considered case-by-case in particular [85], [209].

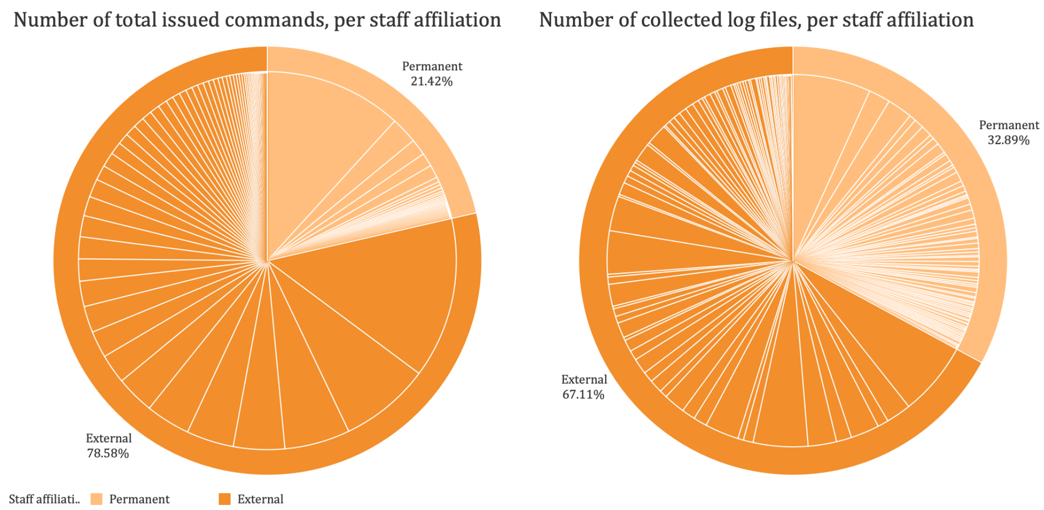

Figure 31. The number of log files and issued commands per staff affiliation.

Clustering results of the logs per individual user are presented in Figure 32 to comprehend the users' BIM activities during the data collection period. Logs under Major and Minor Clusters contain a higher average number of commands and thus have a higher nominal contribution. In contrast, the logs in Dominant and Void Clusters have very few commands in a session; particularly, the Void logs generally exhibit an insufficient amount of execution for significant modeling work.

In light of the factors above, we experimentally classify users into four groups associated with the cluster groups. The proficient user group (G1) refers to the users who nominally contribute the most to the task with the Minor log, Collaborative group (G2) means users who do not hold the Minor log but bind to the Major log, Contributing (G3) is for the users who hold the Dominant log, and General (G4) represents users who only carry the Void log. All users except User 086 own the Void log. All Proficient users have Void, Dominant, and Minor logs, but few are without Major logs (036, 039). A small number of users do not have dominant clusters, whereas all Collaborative users have Major logs.

In the following, we will focus on these four user groups and their affiliations to examine the meaning of this classification.

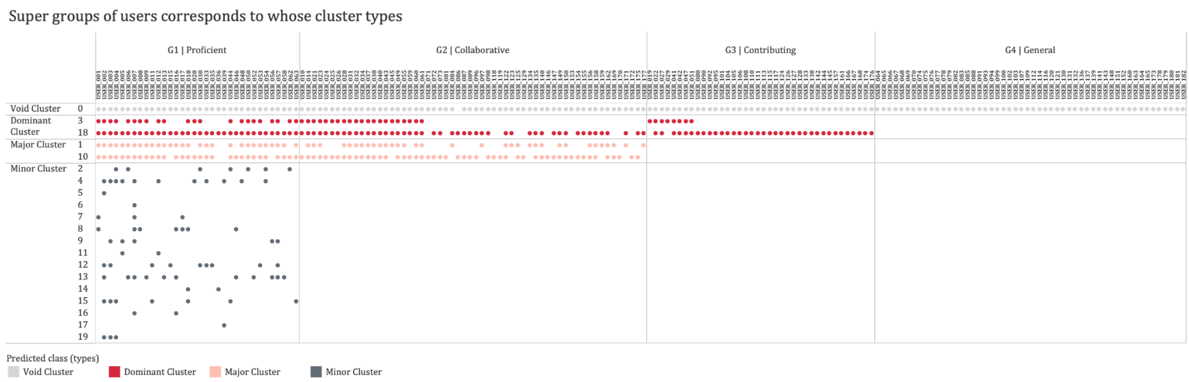

Figure 32. Supergroups of users correspond to whose cluster types.

The bar charts in Figure 33 show an aggregated ratio of the command types for the respective user groups. The commands were categorized into seven types: Modeling commands and Drawing commands for direct contribution to the modeling progress, Editing commands and Save commands for indirect contribution, Import/export commands and Workset configuration for functionality required for collaboration, and Miscellaneous for the rest.

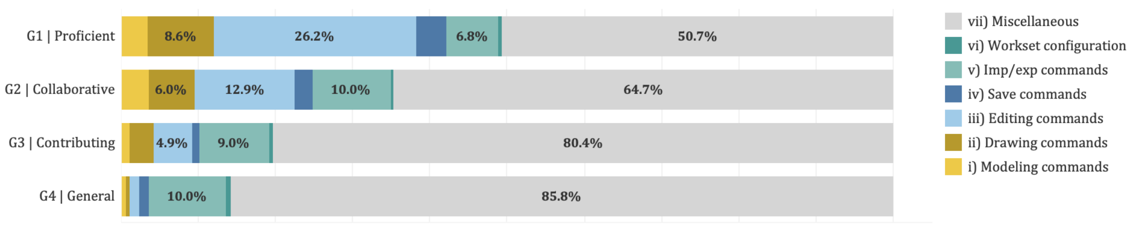

Figure 33. The ratio of command types per user supergroups.

While the Collaborative users show more Miscellaneous commands that do not indicate meaningful contribution to project progress, the proportion of commands for modeling and drafting are comparable to the top users. The difference lies in its composition ratio’s lesser number of editing commands. Accordingly, there seems to be little significant difference between the G1 and G2 users in terms of model creation, and the difference between these users appears to be largely due to editing and modification.

On the other hand, the percentages of modeling and drafting commands stayed low in G3 and G4, and the non-modeling commands (total from iii to vii) exceeded 90%. Only 0.5% of modeling commands were performed by G4 users, indicating that they hardly engage in substantial modeling work. However, the Import/export command displays relatively high values, suggesting that some users execute various settings necessary for collaboration rather than modeling itself.

Despite the fact as seen above that External personnel supply most of the activity on BIM, it is intriguing to notice that there are no prominent differences between External and Permanent in the average number of commands per session in each users' supergroup (Figure 34). This observation indicates that the number ratio within these supergroups causes the overall skew in the workload ratio toward External personnel.

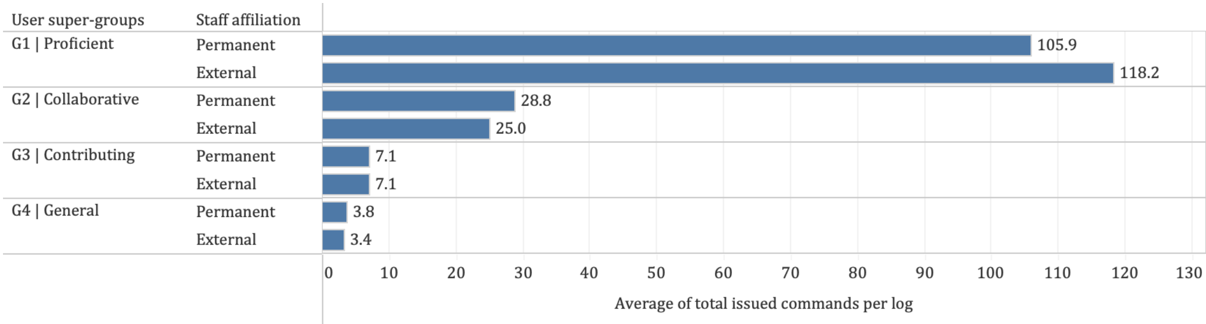

Figure 34. Average of total issued commands per log, categorized by user supergroups and affiliation.

We will analyze the data grouped by projects to understand the responsibilities of the users in the actual project. Eight Revit projects had more than three members involved during the data collection period. Other projects were not captured here because they mainly used other BIM software such as Archicad, were at an early design phase, or were relatively small in scale. The analysis illustrates the work split among the 50 users assigned to these projects.

The bar charts in Figure 35 depict the total count of issued commands during the data collection period based on the affiliation of the project team members, divided into Permanent and External staff. The External staff executed more commands in all projects except Project F, prominently in Projects B, C, G, and H. It is noteworthy that the portions for External staff were all carried out by one to three staff members.

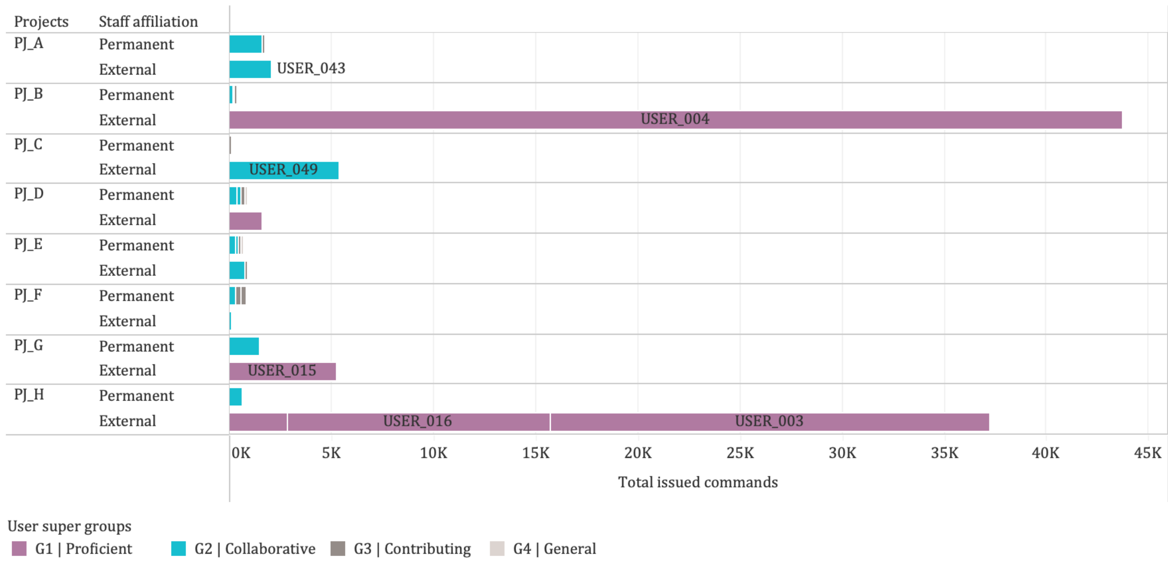

Figure 35. Average total issued commands per staff affiliation and projects.

Cross Analysis and Identifying Keystones

As a next step, the authors further investigate the affiliation and supergroup of the staff assigned to each project. A cross-analysis is conducted to estimate their project contribution outside of

Revit. Figure 36 reports the total time dedicated to each of the six software sessions per project, in addition to the team members' affiliation, department, and supergroup.

Most projects have G1 or G2 BIM staff, who are the driving force for the BIM implementation. Other staff are designated as G3 or G4; nevertheless, their BIM contribution is not necessarily low, as these users may also utilize Archicad or Rebro for considerably more time.

Here is where the G2 staff comes into focus. While the G2s contribute more to modeling, their per-session average count of commands remains lower than G1s. Their Revit utilization time also follows a similar tendency. However, these users recorded greater usage time than average in other software. Several users primarily rely on integrated environments such as Navisworks and Solibri.

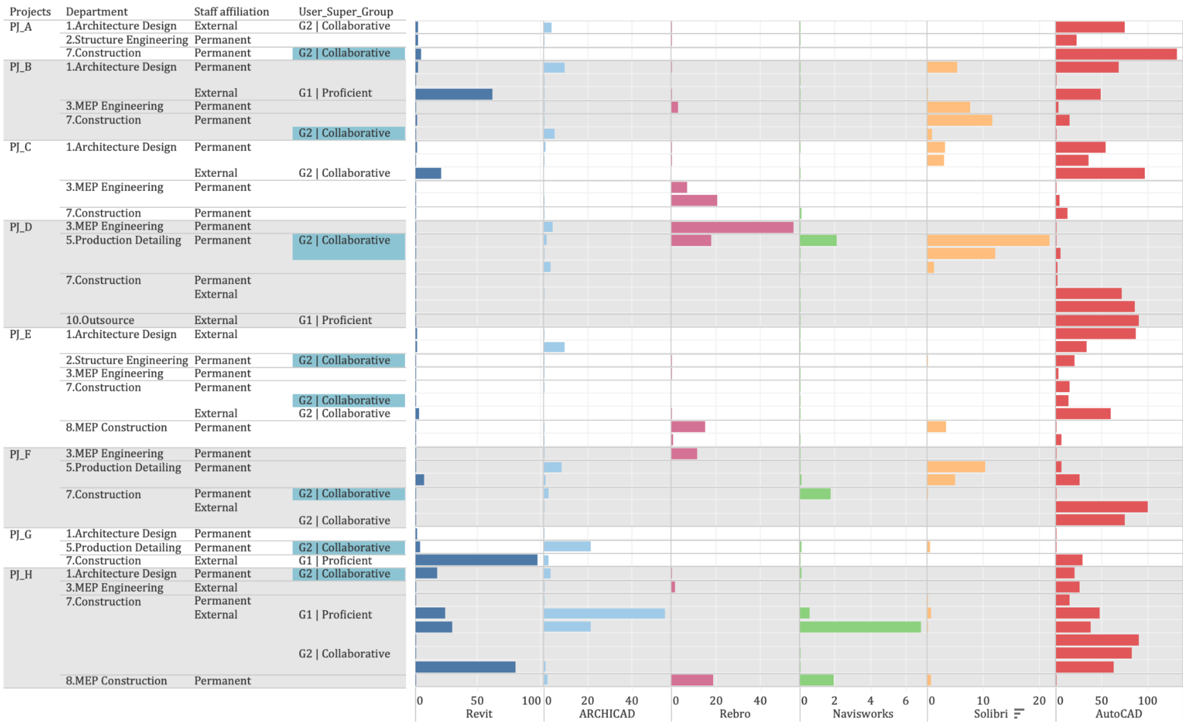

Figure 36. Project staff, supergroups and aggregated software session times.

The number of members within the four supergroups is tabulated by their affiliation and department in Table 16.

There is only four G1 personnel (4.7%) in Permanent staff, but 30 in External personnel (30.6%), which supports the previous projection that the main modeling workforce is from External personnel. Nevertheless, the Permanent staff classified as G2 accounts for 31% of the total, comparable to the 32.6% of the External staff. Few G3 and G4 users can be acknowledged because the External personnel is mostly BIM operators. Nevertheless, as mentioned in the previous section, it cannot be immediately concluded that this personnel is necessarily low in BIM use since they often have a high degree of non-Revit use.

The lower overall BIM utilization by Permanent staff is not because the utilization is sluggish overall, but because there is relatively few G1 personnel. Therefore, the G2 personnel will likely bridge the workflow inside and outside the project.

Table 15. The number of data donors per department and affiliation.

		Permanent				External				Grand Total
Section	Department	G1	G2	G3	G4	G1	G2	G3	G4	
Design	Architecture Design	1	2	5	6	6	6	4	1	31
	Structure Engineering		7	7	1	4		1	2	22
	MEP Engineering		1	3	4		1	1		10
	Computational Design	1	4	1	3		1	1		11
Construction	Production Detailing	2	5	3	1	2	5	1	1	20
	Quantity Survey				1					1
	Construction		6	2	6	8	10	3	6	41
	MEP Construction		1	1	6					8
Administration				1	3		1	1	2	8
Outsource						10	8	3	9	30
Grand Total	Total	4	26	23	31	30	32	15	21	182

A plot of the relationship between the accumulated Revit session time and the total executed commands, Figure 37, shows a strong correlation between the two; the overall distribution of G1 – G4 is generally in line with the intensity of software use, while the distribution of G2 and G3 intersects with each other. This pattern indicates that Collaborative users such as G2 are difficult to stratify from one-dimensional information alone (simple metrics). It is appropriate to use machine learning approaches such as clustering to identify them.

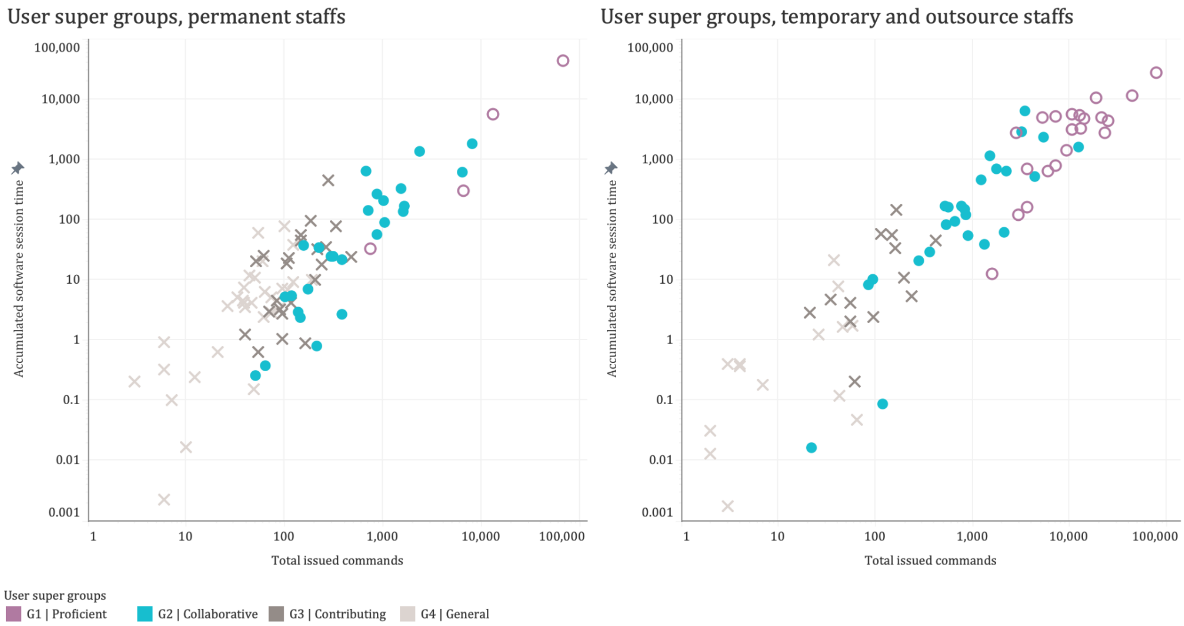

Figure 37. User supergroups plotted the total issued commands and accumulated software session time (Revit).

Verification by Interviews

Given the prerequisite for collaboration with BIM Operators, expanding the G2 hierarchy of Permanent staff is crucial to the growth of BIM. It is helpful to verify the mining results by investigating the cooperative relationship of Permanent staff classified as G2.

Semi-structured interviews were conducted with 6 of the 26 G2 Permanent staff members who consented to participation. The demographic information of interviewees is tabulated in Table 17, and the interview guideline is as detailed in Appendix A. Interviews with each user lasted one hour and were conducted via online calls using Microsoft Teams. The purpose and methodology of the study were announced in advance. However, the analysis results were not communicated to interviewees to avoid bias; instead, they were reported to interviewees who requested them after the process. The results were organized using an analysis template with a pattern coding technique and tabulated using the most important themes.

Table 16. Interviewees' demographic information.

#	Interview date	Affiliation	Position	Experience in AEC
1	July 10, 2020	Architectural design, Permanent	Project architect of two residential design-build projects	> 3 years
2	July 2, 2020	Architectural design, Permanent	Project architect of a complex high-rise, design development	> 4 years
3	June 29, 2020	Construction Planning, Permanent	BIM technical support for ten (10) construction projects	> 12 years
4	June 30, 2020	Construction Planning, Permanent	BIM technical support for nine (9) construction projects	> 10 years
5	July 2, 2020	Structural design, Permanent	Structural engineer of a commercial design-build project	> 11 years
6	July 8, 2020	Architectural design, Permanent	Project architect of an office design-build project	> 14 years

A common thread among the interviewees was that they always collaborated with BIM operators who split the work under their division's domain. The operators' skills were not always superior - employees were occasionally teaching them. A collaborative relationship existed in which the operators handled the principal modeling tasks, and G2 personnel consistently ensured that the External operators stayed focused on the BIM tasks (Table 18).

Table 17. Availability and role of the BIM operator in projects.

Question	Drafted results
Model co-creator	● (#1) A BIM operator (External). ● (#2) Two BIM operators (External). ● (#3) Seven BIM operators (all External). Some operators are skillful in visual scriptings such as Dynamo or Grasshopper or real-time rendering by Lumion or TwinMotion. ● (#4) Five to ten BIM operators (all External) ● (#5) A BIM operator (External) and another Permanent structural engineer ● (#6) A BIM modeling firm (External)
Project model contributor	● (#1) The BIM operator undertook most modeling work, who has experienced decades in the industry and is especially skillful for detail design and construction documentation. ● (#2) The BIM operators exclusively undertook the modeling and drawing tasks. ● (#3) The BIM operators. Upon receiving the project request, the interviewee assigns seven BIM operators. ● (#4) The BIM operators, unless the task is highly urgent. Some operators are to be trained before being deployed to the construction projects. ● (#5) The modeling tasks are mostly done by the BIM operator. As the permanent staff, the engineer reviewed and verified the model against the design and calculation results. ● (#6) Though the modeling process was mainly self-service until the schematic design, some repetitive tasks like designing staircases are shared with the BIM operators. In the detail design phase, the drawing-related tasks are largely outsourced, and the Permanent staff concentrated on project communication to eliminate the informational inconsistency.

Although each G2 employee responded that the External BIM operator performs most tasks, they still complete certain tasks independently. Particularly for architects, this included the production of perspective images to communicate design intent and submission drawings that demanded specific knowledge; for constructors, this included urgent tasks that imposed a deep understanding of project contexts.

All respondents viewed the presence of BIM operators positively and stated that their collaboration could benefit the project by allowing employees to specialize in tasks that cannot be outsourced. Through their own project experience, the respondents pointed out that the employees themselves should not undertake the same level of work as the operators but should acquire the same level of knowledge. The rationale for this point was primarily the need to ensure proper project communication and cooperation and the importance of being respectful to experienced BIM operators (Table 19).

Finally, it is intriguing to note that all interviewees initially stated that they were uncertain about why they were selected for BIM-related interviews because they felt they made no significant contribution to BIM. They were aware that their BIM workload was not as large as that of the operators on the project, and hence they did not consider themselves worthwhile BIM talents for the company.

Table 18. BIM collaboration scheme.

Topic	Drafted results
Role of project architect as Permanent staff	● (#1, #2, #6) Rendered images to visualize architect impression ● (#1) Submission documents to the authority clearance ● (#3, #4) Communicational support. Project requests often require to be decomposed for the operators to execute. Permanent staff can swiftly understand the background context and interpret the required deliverable precisely.
Need for BIM operator	● (#1) BIM operator is ideal to have in any project. Permanent architects could carry out quick changes, but gaining BIM skills during the project is challenging. ● (#2) BIM operator is vital for BIM project regardless of project scale because Permanent staff should spend most of the project time for decision making ● (#3) The need for a BIM operator is parallel to CAD. Permanent staff must be responsible for some tasks, including the client's decision-making or the authority submission. BIM operators need supervision to connect with the project need appropriately. ● (#4) Although the central technical support for BIM will be diminished over the years, BIM operators will be in need in the future. Reducing communicational stress is necessary for a better relationship with each other. ● (#5) Regardless of whether they are BIM technicians or not, supporting staff are vital for timely project progress. The works of modeling, coordination, engineering, and documentation must be balanced in total. The more skillful BIM staff is, the more Permanent staff enhances engineering expertise. ● (#6) Most projects in general contractors require collaboration, including BIM, in terms of scale and complexity. BIM collaboration is inevitable to meet high expectations for on-time delivery, especially during the detail design phase.
The cooperative relationship with BIM operators	● Permanent staff should equip intermediate BIM skills to enable smooth communication with BIM operators. ● Insufficient BIM skills will lead to a lack of respect for skillful BIM operators. ● Permanent staff should concentrate on the tasks where they are fully responsible. Some tasks can be shared with the External staff for timely project delivery. ● While technical challenges in BIM will be transitionally resolved, collaboration with the BIM operators will have been expected to pursue additional value to projects.

Keystone Species Discovered by Log Mining

All participants were stratified into four clusters from G1 to G4, corresponding to the four superordinate clusters, based on the results of VBGMM clustering. While some users classified as G4 had only void logs showing limited contribution, G1 users with high contribution had logs corresponding to all the superclusters. The G1 group was the one who intensively performed the modeling work, with the distribution being heavily concentrated on External personnel. The differences in modeling duties between Permanent and External personnel were evident from the collected logs. Thus, there is no question that External staff undertakes most of the modeling work in this ecosystem.

G2 employees utilized BIM less intensely than the G1, hence their contribution to the project BIM was relatively low. Unlike the G3 and G4 groups, however, the percentage of modeling-related commands is comparable to the G1 group, indicating that a substantial level of contribution to modeling progress is observed. This composition implies that the G2 personnel has a reasonable degree of skills and literacy in BIM. Furthermore, the G2 human resources were widely spread among Permanent and External employees.

The abundance of G2 users in both affiliations is worth reiterating. At least one G2 personnel was identified in all but a few departments. Larger organizations tend to organize a promotion department to consolidate and assign BIM personnel. It was considered reasonable to enhance the efficiency of human resource utilization. This strategy may be well-suited for task-specific personnel such as G1 talents. On the other hand, G2 personnel, who would be pivotal in collaboration, are likely to arise in each department from the respective necessities. When highly specialized personnel are intensively placed, it would be preferable to appoint collaborative users like G2 broadly.

The project-level analysis also revealed that the G1 workforce is the primary promoter, but simultaneously, the G2 workforce occupies a position as a secondary BIM driving force, including a bridge to other software use.

Since it was assumed that the G2 Permanent employees were the keystone species of the project, the verification interview was conducted. As a result, it was discovered that they positively viewed the collaboration with External personnel and acquired BIM knowledge to handle very important tasks independently and respectfully interact with them. It is noteworthy that they did not perceive themselves as occupying an important position in its BIM promotion. Figure 38 depicts the concept of keystone species in the ecosystem.

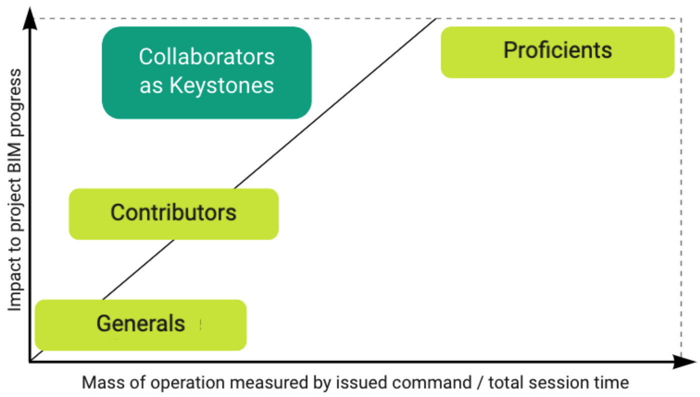

Figure 38. Collaborators as the keystone species in the project BIM ecosystem.

Implication of the Keystone Species in Japanese AEC Ecosystem

The BIM operators often have more years of experience and domain knowledge than employees. Therefore, to achieve cooperative collaboration regardless of job responsibilities, they must not be just in a supervising position but willing to acquire and achieve the same level of knowledge. In a high-context environment, detailed work instructions are often omitted, and fast project communication is required. However, the exact interpretation of the content is difficult for External personnel. Therefore, employees who can conscientiously understand the content must act as interpreters who also understand the content of the BIM work.

Large general contractors have led the spread of BIM in Japan. Most activities are undertaken by External personnel hired on a short-term basis, and Permanent employees are almost exclusively assigned to tasks of higher importance to the project. Nonetheless, Permanent employees must possess adequate BIM knowledge and experience to ensure appropriate direction and approval. It is extremely valuable for general contractors to strengthen the G2 staff since expanding the G1 workforce is hard to achieve.

BIM and CAD operators often have more years of experience and domain knowledge than the average Permanent project member. In order to establish cooperative collaboration regardless of job responsibilities, it is worthwhile for them to be motivated to acquire knowledge and strive to attain the equivalent level of knowledge themselves, rather than simply to stand in a leadership position. In a high-context environment, detailed instructions are often bypassed in favor of quick communication. However, the exact interpretation of the substance is challenging for outside personnel. Therefore, employees who can conscientiously understand the instructions are encouraged to act as interpreters who also comprehend the work performed in BIM.

BIM skills have been focused on modeling; thus, education has emphasized modeling skills. However, in such a collaborative environment, it is more appropriate to focus on the knowledge required for collaboration rather than on specific operations.

Due to the steep learning curve of BIM and the high learning cost of learning to model, it is easy to fall behind when trying to learn it in parallel with practical work. It is important for the company and for the industry to improve the G3 and G4 personnel levels by increasing overall efficiency by focusing on more practically effective points that can be easily applied to the current business.

Even more important is the penetration of BIM to professionals outside of BIM; as BIM is a communication channel, parallel conversations in non-BIM environments are not desirable. However, BIM is oftentimes considered an aggregation or transcription of consolidated information in reality; therefore, the information available from BIM is regarded as unreliable or incomplete. While practitioners should have the right to choose their tools, information sources alienated from project conversations become untrustworthy, or even worth, useless.

The Tokyo office of the data-providing contractor houses more than 2,000 employees, and the members under design and production departments alone easily exceed 1,000. These facts imply that G3s and G4s are not inferior to the whole but are even early adopters when covering the whole professionals. It would be highly realistic to recognize the contribution of G3s and G4s and promote them to participate in a broader range of BIM applications. Arising and consolidating their importance in project communication should positively influence rather than encourage them to become G1s.

Summary

This Chapter conducted a cross-analysis of Revit log files and the aggregated session time of six different BIM applications in a major Japanese general contractor. External staff performed the greater part of the BIM work; most of the Permanent staff's BIM efforts were accomplished by very few employees. The clustering process in BIM log mining yielded four main types of logs. User stratifies these four types of logs; users containing Minor logs are named Proficient users (G1), who have the widest range of log types and contribute the most to the modeling process. The second group, Collaborative users (G2), showed the percentage of modeling contribution comparable to the Proficient users, although the contribution intensity was relatively low. Visual analytics revealed that while Proficient users comprise only a few employees, Collaborative users are widely spread across the organization and projects, comprising about 30% of Permanent and External staff.

Collaborative users tend to use Revit sparingly but spend much time with other software for cross-functional purposes. Among such Collaborative users, it indicated that Permanent staff, in particular, are likely the key to promoting BIM projects.

Semi-structured interviews further explored the common characteristics of Collaborative users. The findings demonstrated that Collaborative users are positive about collaborating with Proficient BIM operators; while they can perform certain operations themselves, they partition the labor to concentrate on their specialty. Notably, their learning motivation was to acquire a comparable level of knowledge for showing respect to the operators. As such, the Collaborative members among Permanent staff are considered the keystone species in the ecosystem of large-scale projects, serving as the pillars of knowledge accumulation and the collaboration hub in organizations.

Chapter 10: Synthesis and discussion

Overview

This chapter integrates and discusses the phased experiments conducted in the empirical chapters.

Although the usefulness of the BIM log had been documented in previous studies, it was unavoidable to revisit the observation of the data itself to strategize how to interpret the collected logs in a collaborative, design-build-based project environment. Next, clustering was introduced to reduce the data dimensionality to have a sweeping view of the data obtained from diverse conditions. Visual analytics methods made it possible to interpret these data in many different directions and capture the segmented data's characteristics. The technique was applied to the larger data from a general contractor, and the mining results were interpreted in combination with other data and interviews. In the following sections, we will discuss the significance of the respective findings and the superiority of the developed methods.

Significance of Collected Data

Each of the datasets constructed for this dissertation has distinct advantages over previous studies.

Dataset 1 was designed to clarify the differences in processes under explicitly controlled conditions. Having multiple ways to obtain a certain result in a modeling environment is common. Especially in architectural projects with many repetitive elements, duplicating and modifying existing elements besides populating new elements is a frequent operation. Therefore, the usefulness of a certain command sequence may not be equally valid for other projects or even other users. Dataset 1 successfully depicted such a situation as a pattern through visual analytics.

Dataset 2 collects data obtained from several organizations of different domains. Previous studies were significantly lopsided towards data provided by particular organizations. Therefore, although the versatility of BIM log mining has been suggested, its utilization, especially in cross-functional organizations, has not been self-explanatory. Also, the role of a single expert can transform over phases, especially in design-build projects. In order to demonstrate this premise, it was essential to demonstrate the usefulness of analysis by the data that integrates the various conditions described above.

Dataset 3 is the largest in the existing study, with a significantly larger number of participants and recorded commands. Most research on collaboration within large organizations is based on sociological approaches; such data-driven and quantitative research opportunity is limited. In particular, it is extremely significant to obtain data that can be commonly interpreted in parallel with the international context to understand Japan's context, which consciously evolved differently from Western architectural culture. The author's advantage of being a doctoral student for career professionals has contributed greatly to acquiring this data.

Significance of Proposed Method

The contribution of the proposed method in this dissertation is immense. In particular, it addresses the fundamental problems of BIM implementation and utilization in the following aspects.

First, the method can be easily automated since it utilizes the BIM logs, the software-generated records. As demonstrated in composing dataset 3, the batch program facilitates the retrieval and transfer of journal files without user intervention. The time required for machine learning is only a few minutes, and it is realistic enough to update the status daily.

Second, the presented result requires minimal BIM knowledge owing to the graphical presentation. The management and executives of organizations often do not possess operational know-how. The visualized activities intuitively unleash effective BIM communication regardless of their skill levels. Project stakeholders, like clients, seek explanations about their return on BIM investment, which often causes a burden for the project team. This approach allows for data-based descriptions of BIM contributions and interpretations tailored to the project structure, thus facilitating a more proactive discussion on project BIM implementation.

Third, the developed method affords dynamic analysis at various levels, including project, organizational, and individual degrees. The analysis context was stationary in most existing research methods; such an approach is probably advantageous where the job definition is clear, and the project presupposes the stringent split of work duties. In Japan, however, job responsibilities are fuzzily defined and can easily change depending on the project circumstances. Moreover, large-scale projects have more participants as they descend through the phases, and each individual's role becomes more limited and specialized. In such a situation, the only universal framing is insufficient. This method assumes a variety of collaboration systems and extracts the weaker signals generated by the collaboration without assuming a correct answer.

The practices pioneered here encourage non-BIM practitioners to become actively involved in BIM-based collaboration. Disinterest can be a major hindrance to project productivity. Especially when BIM tasks are outsourced, the architects and engineers are often only involved in BIM via the output drawings. If those in-house professionals are indifferent to the technical issues arising in the digital workflow and strongly adhere to the existing representation methods, time will be vainly spent on solving non-essential issues, thus hindering the BIM promotion in the project. In worse cases, the cost will exceed the critical point, and the use of BIM itself will be abandoned.

The above examples include the consistency of drawing convention. Even though it has been improving year by year, BIM-based architectural drawings sometimes have inferior expression levels to conventional drawings in the points like line envelopment and line-weight control. Because the poor quality of drawing presentation may trigger doubts about the design quality, not a few designers hope to correct these problems by complying with the existing drawing regulations. In practice, however, it is often necessary to manually fix these line treatments one by one, resulting in more time being consumed just to improve the appearance than the initial documentation work.

It is possible to remedy this situation by accepting new drawing conventions among the project stakeholders amenable to BIM. Figure 39 is an example of a sectional view of a commercial project under the basic design phase with unnecessary separation lines. Once the grey-filled area was defined as the building frame, it became much more readable with minimized touch-ups in the drawing.

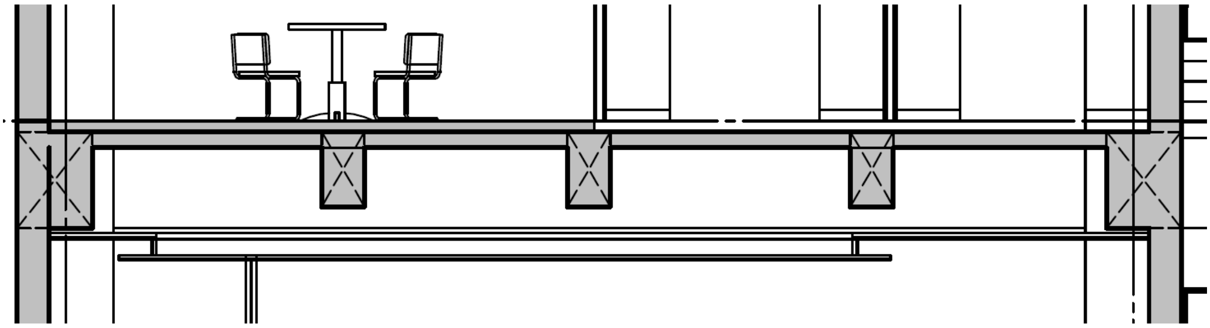

Figure 39. Shortcomings in drawing envelopment expression improved by the hatch pattern.

This kind of improvement does not happen spontaneously. It is devised because of the nature of the software or the effort associated with modeling and drafting and is the result of forming a consensus to supersede existing rules. However, if the architectural designers, decision-makers of the project, do not admit to this enhancement due to their unfamiliarity, the workload for BIM-enabled professionals piles up; the productivity improvement by BIM will be compromised.

Key Findings Through Preparatory and Empirical Chapters

The outcomes from each research step are itemized as below.

Preliminary Study — BIM guideline

- The Japanese government acts slower to mandate BIM use than other developed countries.
- The first MLIT BIM guideline released in 2014 had considerably limited coverage of topics compared to other nationwide BIM standards. The graft into the existing drawing convention spoiled the benefit of native model-based communication.
- A de facto major update was issued in 2020. While various contractual schemes are instantiated, the actionable standards for modeling and coordinating works are yet to be detailed.

Preliminary Study — Existing fact-finding surveys

- **Adoption rate:** The latest survey by MLIT found that 46.2% of respondent organizations have adopted BIM in practice.
- **Expectation to the government:** Despite the high awareness of the industry, the ratio of respondents regarding the government is on the right track were significantly lower than other surveyed countries.
- **Problems in BIM implementation:** The obstacle for BIM in practice was largely recognized as the shortage of skilled practitioners. The survey respondents do not see the lack of ready-to-use BIM standards as a critical issue.

Preliminary Study — Discovery from open discussions

- **Open discussion:** The absence of standardized workflow and off-the-shelf product libraries are pointed out. Some questions concerning the BIM collaboration pointed out that the modeling workforce is outsourced, and thus, the non-BIM architects are potentially distanced from the actual BIM workflow.
- **Roundtable discussion:** Since the current architectural education program places great importance on acquiring the professional license, the learning opportunity of BIM is only additionally included. The stressed need from the industry will reinforce BIM-related literacy.

Empirical study 1

- Visual analytics was applied to illustrate the modeling workflow recorded in BIM log files.
- While the expected BIM skill and the sample project information were normalized, the visualized modeling progress displayed a great variety.
- Due to the overwhelming types of commands issued in the session, the dimensional reduction is required to derive the contextual pattern from the aggregated logs.
- The focus on the halts as short non-operating periods provided another pattern of modeling progress. Since the predetermined modeling strategy should minimize them, interpreted as the downtime for productivity, the versatile BIM strategy is indispensable for the industry to bottom-up the effectiveness of BIM implementation.

Empirical study 2

- The clustering estimator was introduced to restructure the collected dataset into a 30-dimensional database. The appropriateness of the number of clusters is empirically confirmed through visual analytics.
- Four cluster supergroups are observed from the cluster sizes and the mean project contribution.
- The visualizations proved the utility of the proposed method by depicting the traits of BIM activities at the levels of command, organization and user.
- The flexibility of the method applicable to the cross-functional BIM team is suitable to investigate the BIM activities in design-build general contractors.

Empirical study 3

- The proposed method scrutinized the dataset collected from one of the representative general contractors in Japan.
- Despite the high reliance on the outsource workforce, a considerable ratio of collaborative users was identified from the affiliations of both the permanent and external project staff.
- Semi-structured interviews revealed that the collaborative users among Permanent staff delegate the modeling work to the designated BIM specialists. Still, they strived to obtain a certain extent of BIM know-how to show their respect to the skillful outsource experts.

- Their project contribution as the communication hub is disproportionately larger than the software use intensity. Those collaborative in-house practitioners can be regarded as the keystone species, which greatly influence the whole ecosystem when removed.
- Despite such importance, the collaborative permanent BIM users did not regard themselves as occupying the core position in the cooperative projects.

Interpretation to the Local Ecosystem

The reality of BIM doers

Statistically, Table 5 in the previous chapter revealed that dataset 3 exhibited a lower average of issued commands per log than the other. This numerical fact implies that the BIM users in Japanese general contractors generally use BIM less intensively than other industry players.

Void logs contained almost no mean contribution to project BIM progress. General users, recorded only void logs, summed up 36.9% of total permanent staff. Considering that the survey target is limited to Revit users and the participants voluntarily provide their log data, the mean BIM contributors among the in-house permanent personnel occupy much less of the permanent staff.

The fact should be jointly understood with another survey; according to the confidence in BIM knowledge and skills examined by NBS National BIM Report 2019, 57% of 988 respondents answered as “confident” followed by “in-between” (23%) [169]. Although it cannot directly draw a parallel, the investigation by Tagashira et al. regarding the implementation of visual programming language for architectural design practice revealed that only 10 to 20% of professionals in organizations utilized the environment by themselves [210]. When the vertical division of labor among the professionals is the case, individual BIM-based work efficiency and career skill development are more likely to be closely interconnected, thus providing a stronger incentive to acquire skills to become G1s rather than G2s.

Unlike previous BIM log mining methods, the proposed method provides a holistic overview that includes inactive BIM users in the analysis. The existing BIM training approach for industry professionals overemphasizes the modeling process, which should be essential to nurturing collaborative BIM users to become proficient. However, it is unlikely to reframe the scope of architects and engineers in Japan as a generalist who also engages with the full-scale project modeling since the conventional CAD workflow is already largely supported by external specialists. Rather, a refined educational program that facilitates cooperation with the modeling workforce will raise the likelihood for contributing (G3) and general (G4) users to become collaborative (G2) users. The tremendous positive influence is expected from such a movement not only because it genuinely attributes the contributions by the outsourcees but also triggers practical conversations to improve the existing BIM workflow.

Impact of Collaborative Users on BIM Communication

The importance of Collaborative (G2) permanent staff is immense. G2s have adequate BIM knowledge and technical conversations with more advanced BIM users. G1s are mostly outsourcees who proceed with the modeling under the permanent staff's direction. Therefore, the engagement to BIM strategies and the project progress of G2s will improve the work productivity and embolden the trust in project communication. Also, since they are permanent staff, they are familiar with the corporate culture and have less difficulty interfacing with any project team member. Non-BIM practitioners will learn about the project BIM status through G2s' activities.

Given that deploying the external workforce is premised, permanent staff should not aim for the G1 level. The permanents are responsible for communicating with external parties, and it is not always achievable for everyone to balance such a chief portion of work with modeling tasks. Thus, the crossover between being collaborative personnel and permanent staff increases the value of this particular group of personnel.

Although G4s or non-BIM staff may be aware of the existence of project models, they lack the skills to navigate or modify them. While they could give instructions to the outsource BIM specialists, technical conversations are hard to happen. Moreover, the checking of deliverables tends to be skewed toward drawing representations. Figure 40 schematically illustrates how project BIM communication occurs in a design-build project. The red arrows indicate BIM-related communication. We can see that BIM communication is concentrated around G2 permanent employees; they are illustrated to play an integral function in the project network.

The ecosystem can be dramatically different or even cease to exist altogether without the keystone species. BIM communication will be severely impaired without G2s. Increasing the number of G2s to at least be deployable to every project is considered the threshold level to enable BIM-based decision-making throughout an organization.

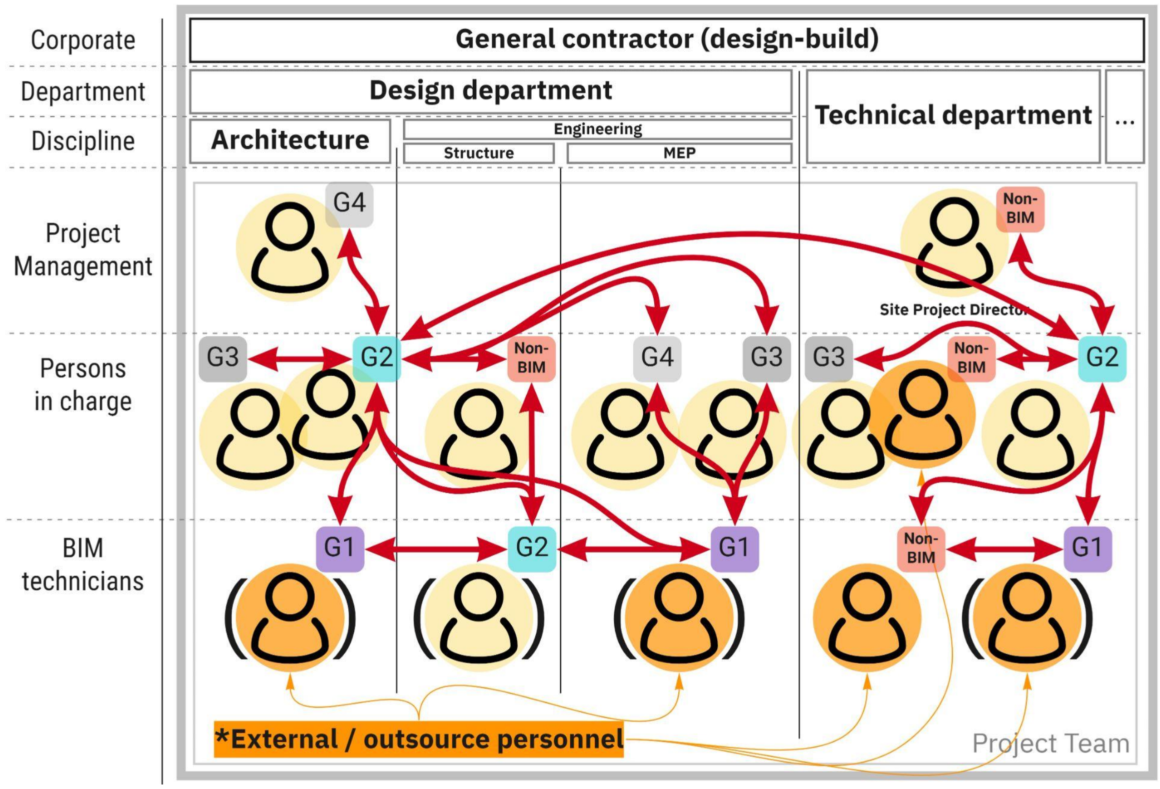

Figure 40. Schematic sample project deployment with the labeling of user supergroups.

The general contractor runs approximately 200 projects concurrently. To deploy at least one collaborative BIM staff for each design and construction, 400 G2 users are expected, equivalent to nearly 30% of the total technical workforce. G2 users currently account for about 30% of the surveyed personnel; however, this is the percentage of personnel limited to BIM-enabled professionals. Even more non-BIM personnel currently exist. In line with Rogers' diffusion of innovation, G2 is expected to disperse from early adopters to the early majority of BIM users (Figure 41). This layer will expand when the technology is sufficiently penetrated; it is theoretically possible for G2 to occupy the entire majority.

Looking back at the age of CAD, the mainstream of design and construction platforms before BIM, there remained many practitioners who are technically unable to operate CAD even after more than 40 years of its commercialization. Those practitioners who still give instructions to operators by sketching seem to exist at 16% or even more, as the laggards of CAD technology. Although BIM is dominant in AEC today, there will be a certain number of people who still do not intend to use it when BIM is entirely replaced by a new concept in the coming few decades.

Being a non-BIM talent does not indicate an underachiever as a building specialist. Experienced personnel who tend to lag in using state-of-the-art digital technology have a wealth of expertise and may use their experience in detail design and material knowledge to produce excellent designs. Many staff members show outstanding abilities in organizing requirements and coordinating opinions rather than modeling and drafting.

Even in the CAD environment, some architects certainly could draw the entire project by themselves; yet they were extremely rare in large-scale projects. Unlike BIM, CAD has been regarded as software for drafting. The idea of completing workflows centered on CAD did exist. Still, it was never widely achieved in the actual business.

Another aspect needs to be combined to understand the G2 talent in BIM. Practical knowledge in design and construction often arrives from other divisions. For example, an architect in a general contractor's design department can achieve more feasible design by augmenting his or her knowledge of estimating, procurement, and production. The acquisition of such knowledge requires learning opportunities through cross-departmental project communication. The characteristics of G2 personnel may be the fragments of their lifelogs that show such behavioral characteristics.

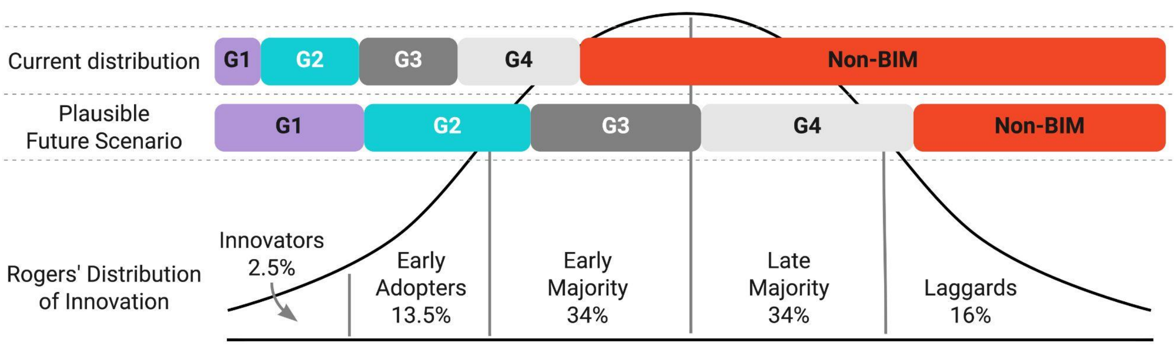

Figure 41. Distribution of user supergroups jointly interpreted with the adopter categorization based on innovativeness, Source:[211], copyright (2008) by the title of publisher.

Positioning of BIM Management

In Japan, project management is most often undertaken by the project owner, designer, or general contractor depending on the project unless it is explicitly assigned to an external party. Traditionally, the client has entrusted the project management to a specialized company, and they have ensured the functioning of the project by appointing a person to be in charge of the management internally.

The ideal form of BIM management varies from one project to another. In addition to domestic cases, international projects compel the formation of BIM teams following contractual requirements. However, issues related to streamlining the project process are not readily apparent when fulfilling the contractual requirements as the primary driver of BIM. Most projects do not appoint an exclusionary BIM manager, and the project leaders themselves take on its responsibility. However, models never evolve independently: they need to be reviewed daily, and those in responsible positions should make design decisions on models.

In cases like the Japanese construction industry, where a cooperative process is a prerequisite, the labor split does not completely follow the functional separation but is defined broadly and vaguely according to the duties and authorities. As with the conventional practice in construction, although subcontractors may be responsible for specific tasks, the architect at the center is expected to be the final responsible one and be in a position to supervise the project comprehensively.

Incentivizing keystone BIM players

Furusaka pointed out from his visitation to the construction project that Technical education for on-site technicians in Japan is accustomed to the lifetime employment system, which is not a modularized training program. The knowledge and experience gained in situ become the expertise of the dispatched staff, not of the company's in-house members. It will further hollow out the technology of general contractors [212].

What is indispensable for in-house permanent employees in large-scale organizations in this context is not to model everything themselves but to attain fundamental knowledge and to maintain a flat and cooperative relationship with an external workforce like BIM operators. Large private companies like general contractors are highly influential in the BIM deployment in Japan. They can improve construction productivity, especially with BIM, when their organizational design and education aim to build a cooperative ecosystem rather than focus on modeling skills.

Specialized business structures have been speculated as a factor inhibiting productivity improvement in the industry. Nevertheless, such an organizational structure is path-dependent, and therefore the trajectory correction is not so easily achieved. Rather, measures to improve efficiency based on the current labor structure division should be considered [213].

Fostering collaborative human resources as the keystone species to connect external and internal human resources is paramount. Monetary rewards can be difficult for Japanese organizations like general contractors, which presume long-term employment to date. Hence, we should search for those collaborative people through data and incentivize them as cross-border professionals. We should delegate a certain level of authority to those self-motivated practitioners to empower the organization to innovate.

Toward Further Workflow Transformation

Metaverse is a combination of the prefix "meta" (implying transcending) with the word "universe" that describes a hypothetical synthetic environment linked to the physical world. The metaverse, a virtual environment blending physical and digital as a computer-generated universe, has been defined through vastly diversified concepts, such as lifelogging, collective space in virtuality, embodied internet, a mirror world, an omniverse: a venue of simulation and collaboration [214].

The context of the metaverse, which has been rapidly gaining attention in recent years, hints at the possibility of redefining the value of BIM in a totally different concept than that of architectural production. The model is a prototype of the building that will eventually be constructed, thus, the digital twins of the as-built facility. Moreover, it also constitutes cyberspace on its own. Currently, immersive experiences such as VR and AR are set up as a destination on a journey from real space, mainly to confirm the forthcoming architecture. In many cases, however, they are mere showcases for the highlights of the development. It is about experiencing the architecture as it will be realized, immersing oneself in the process of its construction, and most importantly, effectively sharing the feeling that it can be changed — if the decision is early enough.

Telepresence technology, which represents the space under planning and where we check-in and wander around, is well established in practice today [39], [215]. In addition, some methods for linking models and comments are well established, such as BIM Communication Format (BCF) [216], a file format that records comments and conversations tagged to their location on the BIM.

During the pandemic, remote participation in AEC projects in Japan has drastically accelerated. Even in construction, where collaboration in real space has been deemed the ultimate form, online collaboration is rapidly being explored. In addition, improvements in the accuracy of transcriptions are making it easier to record all kinds of speech, making it possible to automatically record all kinds of project communication with high accuracy, regardless of online or offline.

There will be a growing movement to value buildings under planning as cyber collaboration spaces built from scratch rather than as unfinished, coarse information. Every record can be archived as a project lifelog, and BIM can form a metaverse as a place for that collaboration. The construction of digital project workplaces and the design of real spaces could occur side by side, often simultaneously. The records of the dialogues will become searchable and analyzable, and ways of using them to increase the value of the collaboration will be explored. The collaborative characteristics found in this study will be extremely meaningful in gaining a foundational understanding of how to extract insights from the project's big data. This can be where BIM goes beyond a database, platform or workflow; to become another universe.

Limitations of the Research

This study concentrated on a single general contractor. Thus it is not obvious if the results apply to other organizations in the sector. Despite the plausibility of the method, obtaining employee attributes besides software logs is not always easy. Many organizations declined to share their log files due to project confidentiality. For example, some components, such as a radiation generator or a baggage handling system, can hint at the project types or even the client itself. The log files contain hardware information, which some firms consider confidential. Deleting those kinds of information at the data collection stage is desirable; however, this requires running such systems at the data donor's premises. Gathering a plentiful quantity of log files from a limited group of organizations will yield cumulative insights for the topic. Suppose broader data is available to benefit from this technique. In that case, it will be possible to draw clearer trends in the entire ecosystem of Japan's construction industry in a data-driven manner.

The log files are transformed into a comprehensive database, which was vital for the machine-learning algorithm to solidify the clustering approach. Increasing the number of log files enriches the database. The accumulated log files can transform into teaching data for supervised machine-learning, by which the results over different projects and organizations become comparable. Further research is encouraged to enhance the quantity of data from large-scale projects to solidify the findings and discover more details of non-modeling activities. Since the number of clusters is non-deterministic in the clustering problem, the adequate number of clusters is not self-evident and must be determined by study results. The number adopted in this study is consistent with providing a broad overview of activities consisting of multiple BIM organizations. However, the optimal number of clusters needs to be further examined.

Lastly, the limitation lies in the log mining of other software. The integration of structural analysis or special equipment engineering will not happen even for central BIM authoring software such as Revit; BIM must be an open platform to accept the interoperation of multiple professional programs [217]. There needs to be a supplemental system for software programs that do not leave usable logs to collect the operational data. Yarmohammadi et al. leveraged an application programming interface (API) to collect the modeling data in real-time from Autodesk Revit [218]. Despite several studies on IFC, the mining methods for most software without operation logs are still unexplored; thus, a procedure to extract the equivalent knowledge from Revit has not been successfully implemented. In this study, we attempted to consider this area by analyzing the time spent; however, as seen earlier in the study, the software session time is not necessarily proportional to the BIM contribution. Alternatively, users who show regular collaboration with other users may be considered keystone users regardless of their usage time.

Summary

This chapter outlined the findings from the earlier chapters. The implications of the discoveries for the Japanese collaborative environment, the significance of the proposed method, and its contribution to the existing body of knowledge are discussed.

The building industry has so far responded to these challenges by providing practitioners with operational BIM knowledge. Unfortunately, the learning curve for BIM is steep, and the practitioners will need an enormous amount of time to acquire enough knowledge to build a model. As a result, only mediocre modeling knowledge remains, leaving practitioners unable to acquire the essential BIM expertise for collaboration and communication.

Due to various factors such as organizational disciplines, project scale, and project requirements, diverse BIM capabilities are required for BIM users and teams. As the service they provide to the project changes dynamically along the project timeline, their formations in the environment should change from time to time as needed. The approach proposed in this study is not a metric for assessing individual or group performance but rather a tool for reflecting whether the desired skills and competencies are being provided by benchmarking and comparing others or past selves. The method enables BIM practitioners to design their skills and provide BIM teams with information for their organizational design.

The successful BIM implementation throughout the building lifecycle is still hard to realize. Considering the organizational design and individuals' skills are deeply relevant to the issue, this methodology potentially becomes an indispensable protocol to improve BIM use continuously.

This premise cannot be based on the illusion that a building designer must be able to do everything by themselves, but rather on the basic responsibility of the core project architect or engineer to treat all collaborators with respect and to streamline the entire workflow. Viewing a BIM model from the outside does not provide any insight into the day-to-day workings of the model. Using tools that are understandable to such stakeholders is extremely important to generate more interest through exposure.

Chapter 11: Conclusion

Conclusion for Research Questions

RQ1: Can we decode the cross-functional BIM activity out of data?

- Mining the BIM log file recorded by the BIM software provided extensive insights into the BIM activities occurring in BIM projects.
- The application of visual analytics techniques enabled the projection of data onto the data subspace flexibly according to the interests or problems.
- A considerable amount of information among all available records was not observable only by monitoring the 3D models.
- The obtained plots were intuitively comprehensive for laypersons. Appropriately configured visualization does not demand any prerequisite operational BIM skills.

RQ2: How can we represent the traits of BIM collaboration in projects?

- The partitional clustering algorithm classified overwhelming data dimensionality into a limited number of clusters.
- Multidisciplinary logs collected from ten organizations were thoroughly simplified by four superclusters, which signify different contributions to the project's progress.
- Each analysis based on organization, user, and command represented the respective patterns that can be jointly interpreted with the answers to the questionnaire.

RQ3: How can we identify the "keystones" in organizations?

- A massive dataset provided by a major Japanese general contractor and its subsidiary company was examined.
- On top of the established methodology, supplemental data was included for cross-analysis to reflect the project BIM environment more precisely.
- The aggregated log statistics depicted the in-house professionals' significant reliance on the external BIM workforce.
- The result of log mining stratified the BIM users into four layers. A group of users who are not proficient in operation yet taking collaborative actions was identified and termed as Collaborative (G2) users. G2 users occupied more than 30% of in-house permanent staff and external dispatched staff.
- The interview with permanent G2 staff revealed that they successfully yet unknowingly delegate their modeling tasks to the external experts by obtaining adequate BIM knowledge.
- Considering the disproportionately large influence of G2 despite their nominal contribution, G2 users can be regarded as the keystone species in the project and organizational BIM ecosystem.

Major Contribution of the Research

The contributions of the thesis are immense as the findings contribute to the existing body of knowledge. It also contributes to furthering good industry practice. Namely, the contributions to knowledge and industry include the following.

Firstly, the proposed method extends the existing BIM log mining technique. The vast amount of datasets explored and verified the utility of the proposed method, which combined the visual analytics and partitional clustering algorithm as a novel approach. It should be reiterated that the proposed method applies to multidisciplinary logs, which is essential functionality to analyze the design-and-build projects.

Secondly, the thesis introduces the keystone species concept that became possible by analogizing the BIM environment as an ecology. As the keystone species are the ones who have a tremendous influence on the surroundings once they are removed, the identified keystone species should be nurtured and even augmented to upscale the BIM collaboration.

Last is the exclusive focus on the cooperative relationship in the Japanese AEC industry. Although it was partially recognized that collaborative attitudes are widely seen in the construction field, it was hardly mentioned that similar events happen throughout the project, including the design phase. The research on BIM operators or other external supporters in Japan is still unavailable. Their employment status, roles, contributions, and treatment should be uncovered for further constructive discussions. The architecture can only be established through collaboration; therefore, it is imperative to recognize the existence of such supporters in the project to foster discussions on better collaboration.

Future Prospect

From the research process, the author lists the recommendations for future research as follows:

Introducing BIM log-based monitoring system

The proposed method is never for micromanagement. It increases the transparency of BIM activities for active and reciprocal communications around the models in progress. Also, sharing a dashboard for frequently referenced visualizations enables a wide range of self-checking for users and teams. The operational recommendation, like a shortcut for a particular command sequence or suggestion to use the new functionality, becomes possible by collecting long-term logs and implementing a neural network system. Visualization of BIM activity and contribution enables designing skill-set for individuals and management.

Nurturing keystone species in the organizations

A positive affirmation for the collaborative BIM users has been lacking in organizations. The discrepancy between the form of cooperative relationship and the goal of BIM education primarily caused the issue. On the premise that BIM serves for better communication in large-scale projects, learning objectives should be reconfigured to aim for collaboration with mutual respect among the project members. The learning of modeling techniques typically tends to be endless; limiting the target into the basics and minimum amendment without the help of external specialists reframes the learning process into a feasible one for the practitioners. Instead, enriched case studies for successful collaboration will inspire the professionals to intake the upsides into the projects as low-hanging fruits.

Further study for supporting project professionals, including BIM operators

As the thesis partially revealed, embarking external specialists into the architect's scope of work has been a norm for almost a century, mainly because of the uniqueness of architects' role connected to the historical background. BIM operators in Japan can be understood in line with this context. However, their underlying contribution to the influential projects is neither clearly allocated in the guidelines nor thoroughly studied in the academic field. While the research aligned to the preceding ones may be difficult due to the limited online information, incorporating the topic into the industry-wide fact-finding survey seems realistic to yield a satisfactory response.

Industry-wide BIM guideline from successful large-scale projects

It is unlikely that one of the giant players in the industry voluntarily discloses the know-how to the public because the top five general contractors are in severe competition with each other. Therefore, it is reasonable that the government absorbs their success stories and distributes the key factors in standards to alleviate smaller organizations' barriers. Although the professionals from authoritative positions edit currently available guidelines in Japan, the perspective from devoted BIM users is not weighed. Open discussion involving BIM savvy is pivotal to penetrating the practice's industry-wide workflow.

Appendices

Appendix A: Questionnaire

The following questions were used for the study.

Q1: When did you first use Revit by yourself?

Q2: When did you start using Revit for your ongoing project?

Q3: How would you rank your own Revit skill within your firm/organization?
++++ Expert / +++ Advanced / ++ Intermediate / + Basic / Beginner

Q4: Please choose the most helpful resource during your Revit learning process.
Online help, manual, video / Online discussion board, SNS / Book, publication / Asking colleague or friend / Trial and error / Vendor's help desk

Q5: In your average daily work, how much time do you spend on operational troubleshooting?
Almost none / 30 minutes / One hour / One and a half hour / More than two hours

Q6: How would you evaluate your BIM skill as compared with CAD?
Better at BIM / Almost equal / Better at CAD / Neither

Q7: Which of the following best applies to your position regarding decision-making?
NA: I am a student or trainee / NA: I am a consultant / I model with the given instructions

/ I initiate, but it is subject to supervisor's approval / I am the decision-maker

Q8: How many years of experience do you have in the AEC industry (including civil works)?

Q9: How many years have you been in your current company/college/organization?

Q10: Which output do you produce the most in BIM or in work based on BIM geometry?
Design drawings / Detail drawings / Construction, shop drawings / Perspective images / Navisworks model / Revit model

Q11: In terms of your project involvement, which of the following actions best match your role?
Creating models / Updating or amending others' models / Auditing models / Extracting information out of models / Using models for reference / Coding on models

Q12: In your recent projects, which status best applies to the project BIM model versus project drawings?
Model is the most updated / model is as updated as drawings / Model is the most updated, drawings partially up to date / Drawing is the most updated, the model is catching up / Drawing is the most updated, the model is for reference / Model is abandoned / Using the model as a test case

Q13: Which of the following best applies to the models in your recent projects?
I work on a single model per project / I work on a model in federated models / I coordinate multiple models

Q14: Which description best describes the model(s) you work on?
Models of the project that I am in charge of / Models of the project that I provide BIM support for / Miscellaneous models of your firm/organization's projects / Miscellaneous models, various authors / Non-project, sandbox models

Q15: Please choose the task that takes the longest time to perform in Revit.
Model creation / Documentation / Model amendment / Model checking / Rendering, visualization / Data conversion

Q16: Do you use Dynamo in your project?
No, I have not used Dynamo / Yes, I leverage codes made by others / Yes, I code by myself / Yes, I create codes with programmers

Q17: About what percentage of your time working in Revit do you stay in 3D views?
0-5% / 5%-10% / 10%-15% / 15%-20% / 20%-33% / 33%-50% / >50%

Q18: How has your experience been with Revit?
5: I strongly like it / 4: I like it / 3: Neutral / 2: I dislike it / 1: I strongly dislike it

Q19: Which of the following is your discipline?
Architecture / Structure / MEP / Construction / Others

Q20: Please select your job title.
CEO, President / Manager, Director / Designer, Engineer / Modeler, Coordinator / Consultant / Student, Trainee

Appendix B: Semi-Structured Interview Guide

Start of interview

- Introduce the interviewer to the interviewee.
- Provide a background of the interview:
    - The aim is to verify the discoveries from BIM log mining conducted on the software records across the firm, including the interviewee.
    - The reason for selecting you as an interviewee is because the interviewee's BIM activity may represent certain tendencies in terms of organizational BIM implementation.
    - The interviewer requests the interviewee's project and situation. Please answer your personal experience and opinion; it needs not consider the broader perspective.
    - The mining result will not be disclosed since the analysis is in progress; however, the interviewee will share the published article afterward.
- There will be an opportunity for questions at the end.
- The interview begins when the interviewee understands and agrees with the above condition.

1. Interviewee personal details
    - 1.1. Name:
    - 1.2. Position: (management / project architect / BIM promotion team / BIM operator)
    - 1.3. Qualification: (licensed architect / licensed engineer / none)
    - 1.4. Years of experience:
2. Project details the interviewees were in charge during the log collection period
    - 2.1. Project name:
    - 2.2. Project location:
    - 2.3. Project owner:
    - 2.4. Type of project: (residential / commercial / industrial / educational / ...)
    - 2.5. The number of floors:
    - 2.6. Estimated project duration in month: (levels of aboveground / levels of the underground)
3. Use of BIM software (Revit)
    - 3.1. What was the primary reason for implementing BIM in the project?
    - 3.2. Who was the decision-maker to adopt BIM for the above?
    - 3.3. Did the project have the BIM execution plan (BEP)?
    - 3.4. To what extent was the project required to utilize Revit or other BIM applications?
4. Role of interviewee
    - 4.1. Have you been navigating Revit on your own?
        - 4.1.1. If yes, have you been modeling by yourself?
        - 4.1.2. If not, how have you been proceeding with the project by Revit?
    - 4.2. Have you had anybody else who (co-)created the project model?

4.2.1. If yes, were they the dedicated BIM operators?
4.2.2. If yes, were they the External staff?
4.3. Was the managerial personnel involved in the BIM process?
4.3.1. If yes, were they supportive of implementing and leveraging BIM in the project?
4.3.2. If not, what did you observe as the chief reason?

5. Contribution to modeling
   5.1. Who most contributed to the progress of the modeling?
   5.2. How do the rest project members collaborate with the model contributor identified in Q5.1?
6. Project self-evaluation
   6.1. What was the benefit of Revit identified throughout the project?
   6.2. Did the BIM implementation progress cooperatively?
   6.3. In your opinion, do you think it was ideal to proceed with BIM in such collaboration scheme mentioned in Q4?
   6.4. What was the primary factor that contributed to enhancing project productivity?
7. Shortcomings and proposals for future projects
   7.1. What were the shortcomings identified in implementing BIM to the project?
   7.2. Do you think you should undertake more modeling roles than current ones in future projects?
      7.2.1. What is the reason for the above opinion?

End of interview

- Ask the interviewee if they have any further information to share.
- Ask the interviewee for further questions
- Thank the interviewee for their time and help

Appendix C. List of Author's Academic Contribution

Journal publications

The peer-reviewed article below has been published as first author:

- ISHIZAWA Tsukasa and IKEDA Yasushi (2021), Visual log analysis method for designing individual and organizational BIM skill. 建築情報学会論文誌 Vol.1, a1–a21. https://doi.org/10.50926/ais.1.1_a

The preprint below is currently under the process of peer-review:

- ISHIZAWA Tsukasa and IKEDA Yasushi, Keystones in Building Information Modeling, Journal of Information Technology in Construction

Conference Publications

The author has given two oral presentations at the following conferences:

- ISHIZAWA Tsukasa and XIAO Yahan and IKEDA Yasushi (2018), Analyzing BIM protocols and users surveys in Japan, The 23rd International Conference on Computer-Aided Architectural Design Research in Asia 2018, 2018-05-17
- ISHIZAWA Tsukasa and IKEDA Yasushi (2018), Analysis of Modeling Approach through BIM Log Files, The 41st Symposium on Computer Technology of Information, Systems and Applications, 日本建築学会, 2018-12-17

Apart from the above works, the author contributed to the following manuscript as the second author:

- SATO Gen, ISHIZAWA Tsukasa, ISEDA Hajime, and KITAHARA Hideo (2020), Automatic Generation of the Schematic Mechanical System Drawing by Generative Adversarial Network, Anthropologic: Architecture and Fabrication in the cognitive age - Proceedings of the 38th eCAADe Conference - Volume 1, 2020-09-16

Other contributions are listed herein:

Book

- 小見山陽介, 杉田宗, and 石澤宰 et al., 建築情報学へ Towards Architectural Informatics. 東京: millegraph, 2020

Lectures

1. Invited Lecture, デザインスタディーズ・Keio University 慶應義塾大学・2021-11-04
2. Lecturer, デザインスタジオ（都市と建築）・Keio University 慶應義塾大学・2021-10-03～2022-01-18
3. Invited Lecture, 拡張する建築の職能, 建築情報学連続ミニレクチャー・Ritsumeikan University 立命館大学・2021-01-12
4. Invited Lecture, BIM in Takenaka,「建築生産」・Tokyo University of Science 東京理科大学・2020-12-08

5. Invited Lecture, Construction Management, 建設マネジメント論・Keio University 慶應義塾大学・2020-10-30
6. Invited Lecture, BIM in Takenaka, 建筑信息模型在竹中工務店・Zhejiang University 浙江大学（杭州、中国）・2019-11-06

Invited talks at industrial conferences

1. Benchmarking the Flavors of Design-Build and How to Overcome the Contractual & Cultural Barriers to Make it a Success・Invited Panel・Advancing Preconstruction 2021, Dallas TX・2021-08-31
2. Data-driven Design and Build, Opportunities and Challenges・Invited Speaker・Built Environment Technical Webinar Series (IDD Track) Innovation in Digital Design and Construction, Singapore・2021-08-24
3. Understanding the Implications of Computational & Generative Processes on the Design Workflow・Invited Speaker・Advancing Preconstruction 2020, Las Vegas NV・2020-11-05
4. BIM・コンピュテーショナルデザイン・データが紡ぐ未来・とちぎ建築プロジェクト2019 基調講演・2019-11-26
5. Workshop between Bundesministerium des Innern, für Bau und Heimat, Bundesministerium für Verkehr und digitale Infrastruktur (Germany) and Ministry of Land, Infrastructure, Transportation and Tourism (Japan) ・ドイツ連邦内務・建築・地方自治省と日本国土交通省とのワークショップ・Tokyo・2019-11-05
6. Collecting & Leveraging Data to Inform Future Designs and Make Data-Driven, Performance Based Decisions・Advancing Computational Building Design 2019・2019-07-31
7. 「建築が変わる／仕事が変わる」・第42回 建築士事務所全国大会・日本建築士事務所協会連合会（日事連）・2018-10-05
8. The 1st Achievement of Building Confirmation by BIM & Cloud Service・buildingSMART International Standards Summit, Regulatory Room・2018-03-27

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