A REVIEW OF DESIGN RESEARCH IN ENGINEERING PRODUCTIVITY IN THE ARCHITECTURE, ENGINEERING AND CONSTRUCTION (AEC) INDUSTRY

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ABSTRACT
Productivity studies in the AEC industry has gained significant attention in the past decade, however the impact from actual industry application has not kept up. This could be attributed to the focus on construction productivity instead of engineering productivity. This paper presents a systematic literature review on engineering design productivity in AEC industry focusing on design research method applications.

Keywords: Design process, Organizational processes, Design management, Engineering Producivity, Engineer Performace

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1 INTRODUCTION

1.1 Engineering productivity in the AEC industry

This paper aims to identify factors and characteristics in the design processes within the Architecture, Engineering and Construction (AEC) industry that affects engineering productivity. The review focuses on engineering productivity that includes design activities required by architects, engineers and contractors to achieve required building plan drawings for the actual construction of the building. The building design stages considered are highlighted in the red box in Figure 1 below.

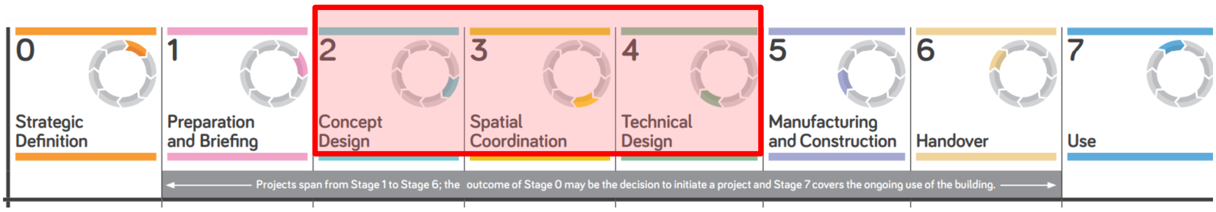

Figure 1. Building project stages within the RIBA plan of work 2020 considered in study (Royal Institute of British Architects 2020)

Through collecting these factors from both academia and industry reports, this study wishes to understand what affects engineering productivity in building design and also verify if it is coherent with observations of the industry. To do so, this review will identify patterns in the literature that explains (1) research interests in this area with time (2) sources of publication reflecting audience in this area of research (3) extent of stakeholder/ multi-disciplinary study of topic (4) particular phase study in AEC industry.

1.2 Background

As reported by McKinsey Global Institute, the construction sector is one of the largest in the world with about $10 trillion spent on construction-related goods and services every year. However, the industry suffers from problems in productivity with global labour productivity growth averaged only 1% a year over the past two decades, compared with growth of 2.8% for the total world economy and 3.6% in manufacturing (Barbosa *et al.*, 2017).

Anecdotal evidence from the first two authors' observation as practising engineers in the industry further suggests that engineering design processes in the offices also contribute to the productivity problem. As building projects are complex and large, the number of stakeholders involved are substantial, corresponding large amount of information and decisions. The complicated and repetitive design workflows often result in delay and poor design quality if not done properly. The anecdotal evidence from the first author's experience further suggests that the three most significant contributing factors to engineering design productivity are:

1. Multi-stakeholder and multidisciplinary nature of the design process
2. Importance of design co-ordination and input in the conceptual design stage
3. Technological advancements in the collaboration/ information exchange processes

2 STUDIES SELECTION

Journals, conference papers, books, theses and industry reports were selected, focusing, first, on design research methods, then other research approaches that relate to engineering productivity in the AEC industry.

2.1 Research methodology

A systematic literature review was employed, and the results presented in this paper. The data search begins with first, the search string TITLE- ABS-KEY ("engineering productivity" AND "AEC industry) applied to search for journal, conference papers and industry reports.

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2.1.1 Selection criteria

The selection criteria and procedures at this stage are such that works entirely concerned with construction productivity are excluded from analysis as this paper focuses on engineering productivity in building design (focused sources).

As initial literature search with the first criterion returned very little work, it was relaxed to include works addressing design research in engineering productivity in other fields. They are included as it is valuable to apply the methodology to the AEC industry.

Works addressing design research of the AEC industry/building design were also included as design research methods typically employ design process modelling which builds the framework in most productivity studies. (comprehensive sources)

2.1.2 Selection procedure

Search results were first analysed by reading the abstract of the papers. If the content is relevant, the introduction and conclusion were then read to gain a better understanding. Finally, if the content is deemed to fit the selection criteria, the full paper will be read, and relevant information extracted (see next section).

The next step of the literature review was a backward snowballing approach (Wohlin 2014). References of the initially selected sample were screened and articles were selected according to their relevance (based on their title and content) (Geissdoerfer *et al.* 2020) and the selection procedure repeats.

3 INFORMATION EXTRACTION

3.1 Main information inclusion and exclusion criteria definition

The information extracted from the sources must contain:

- The name of the factor/correlation/measure/influence-factor/success-factor of engineer productivity
- The description of the nature of correlation/relationship

Table 2 shows the list of focused sources that fit the selection criteria described above.

Contact the author for the corresponding summary table for comprehensive sources that were used for further analysis.

3.2 Other information

Other information that could relate to engineering productivity were extracted. These included information are related to the three factors identified in Section 1.3 based on anecdotal evidence of the first author.

Information extracted for analysis include:

- Type of publication (journal/ book/ thesis/ conference paper/industry reports)
- Research methodology (design process model, analysis model, objectives, disciplines)
- Design stage analysed (concept stage/ tender stage/ detailed design/ authority submissions)
- Nature of study (descriptive study/ background/ review/ prescriptive study/ empirical study etc)

3.3 Results representation

Readings were evaluated and categorised into two broad categories- Methodological and Research outcomes.

3.3.1 Research methods

Results were analysed based on the methodology employed in the study of engineering productivity. These include the design process model used to document the building design process, how the model is analysed, and the scope of design that was analysed. For example, different stages of processes would involve different stakeholders for correspondences or approvals and hence this information was extracted from the sources. Multi-stakeholder analysis of the building design process is also more comprehensive as the nature of collaboration and co-operation is a key contributor to productivity. It is also well established in design research that stakeholders influence decision-making processes (Lenssen *et al.* 2010).

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For different design stages within the building design process, engineers engage with other stakeholders and contribute to the design process differently. Section 2.3 discussed the benefits of engineers' involvement in conceptual design stages. As such, research in this area of the design process provides the most value and insight to engineer productivity. In the same context, design stages that result in rework and iteration would have significant research value as discussed in Section 2.5.

3.3.2 Research outcomes

Information extracted was also summarised based on their research outcomes which, from the selection criteria, are the factors that affect engineering productivity. These factors can further be classified into human (design engineer) factors and design environment factors. This paper categorises these factors using the framework adopted by (Hales and Gooch 2004) and summarised below.

Table 1. Summary of design process influences taken from managing engineering design (Hales and Gooch 2004)

Level	Influences
Microeconomic	Market, Resource Availability, and Customers
	Customers (Clients), and Users
Macroeconomic	Cultural, Scientific, and Random
Corporate	Corporate Structure, Systems, and Strategy
	Shared Values
	Management Style, Skills, and Staff
Individual/ Personal	Knowledge, Skills, and Attitude, Motivation, Relationships, Personal Output

4 LITERATURE REVIEW RESULTS

It is observed that most productivity studies in the AEC industry are focused on studying construction-related productivity; however, engineering productivity is rarely studied. Including studies in engineering productivity will then cover the entire process (from concept design to construction stages) and could potentially improve productivity studies in the AEC industry.
Through collecting engineering productivity factors related to building design, the following underlying concepts were covered: concurrent engineering, conceptualisation, construction management and design information flow management. These topics are key concepts and tools that can be applied to studying engineering productivity using design research methods. This section summarises these topics and their relevant literature.

4.1 Design Process Models

Design research methods are mainly focused on mechanical engineering fields. However, a significant paper made comparisons of design methodologies and process models across disciplines (Gericke and Blessing 2011). This paper specifically reviewed research methods and compared the characteristics of design process models in engineering to those in architecture. The design process model identified that is widely acknowledged and referred to in the AEC industry is the RIBA plan of work document/ Architect's job book first published in 1964. Further research on design process models in architecture/building design frequently made references and comparisons to this document.
Further work by (Gericke and Blessing 2012) analysed design process models across disciplines. In this paper, the authors first explained and categorised design process models in engineering. He then analysed a collection of design process models across disciplines, 10 of which are in building design (architecture/civil engineering) and are relevant to this study. The categorisation method will be employed later in Section 4.2.

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Table 2. Summary of works on engineering productivity in the AEC industry

Author	Year	Publication Type	Methodological				Research Outcomes		
			Multi-disciplinary	Nature of Study	Analysis Model	Design Stage	Objectives	Variables	Influences
AlChaer and Issa, 2020	2020	Journal	No	Prescriptive Study	N.A.	Construction and design	Productivity measurement/ score	Repetitive work, Delay, Compensation/ Wage	Corporate
Arashpour and Arashpour, 2015	2015	Journal	Yes	Empirical Study	Mathematical, Simulation	Construction	Analyse impact of variability on productivity	Variability, Rework, Delay	Corporate
Arditi and Mochtar, 2000	2000	Journal	No	Empirical Study	Statistical analysis	All	Statistical analysis of survey on productivity in construction industry	Design reviews, value engineering, contract agreements	Corporate
Brown, 2020	2020	Journal	No	User study	N.A.	Concept stage	Interactive approaches to multi-objective early building design	Design environment, feedback, optimisation tool	Corporate, Microeconomic
Changali et al., 2015	2015	Report	No	Descriptive Study	N.A.	All	Analysis of poor productivity in construction industry from management perspective	Organisation, communication, contractual, performance/ risk/ talent management, planning	Corporate
Crawford and Vogl, 2006	2006	Journal	No	Descriptive Study	Economic Models	Labour	Explain inconsistencies of current labour productivity measures	Stock of capital services, labour services, intermediate inputs, management and organisation	Microeconomic, Corporate
Denis, 1986	1986	Report	Yes	Empirical Study	Survey	All	Matrix organisation of projects enhances productivity	Organisation structure, designer capacities, resource flexibility, cooperation, team atmosphere	Corporate
Ebrahimy and Rokni, 2010	2010	Conference	No	Review	N.A.	N.A.	Validity of current industry engineering productivity metrics	N.A.	
Evers et al., 1998	1998	Conference	Yes	Detailed time study and	Continuous flow developmer	All	Understanding engineers' time allocation to identify opportunities for improvement and further analysis	Variability, rework, complexity, work-in-progress	Corporate
Georgy et al., 2005	2005	Journal	Yes	Empirical Study	artificial neural networks and	All	New approach to predict engineering design performance	Surrounding environment and conditions, engineer early participation	Corporate
Girczyc and Carlson, 1993	1993	Conference	No	Descriptive Study	N.A.	Design	Effectiveness and implementation of design reuse	Productivity, performance, correctness, predictability	Corporate
Jongeling et al., 2008	2008	Journal	No	Case Study	Quantitative time- space anal	Detailed design/ construction planning	Benefits of quantitative analyses of 4D models	Production costs, work spaces, construction operations	Microeconomic
Kim, 2007	2007	Thesis	Yes	Detailed Study	N.A.	All	Development of engineering productivity metrics	Equipment, rework, instrumentation, IFC quantities	Microeconomic
Liao, 2008	2008	Thesis	Yes	Detailed Study	Quantitative analysis	All	Identification of influence factors for productivity improvement, quantitative analysis of information dependencies, relationship between productivity and project performance documentation	Project size, project type, project nature, project priority, work involvement, contract type	Microeconomic
Liao et al., 2011	2011	Journal	No	Review	Data analyses and industry exp	All	Investigate relationships between factors that affects direct engineer labour productivity	Project size, project type, project priority, and phase involvement	Microeconomic, Corporate
Liao et al., 2012	2012	Journal	Yes	Empirical Study	Statistical Analysis	All	Examination of aggregating engineering productivity metrics to project level projects.	Project size, project nature, project type	Microeconomic
Liao et al., 2009	2009	Conference	Yes	Empirical Study	Industry information/ database	All	Develop standardisation approach to aggregate productivity measurement	Project nature, project size, project type, work involvement, contract type, project priority	Microeconomic, Corporate
Liker and Hancock, 1984	1984	Report	No	Empirical Study	Classical work design with su	All	Measurement of factors lowering engineering productivity	Input, machines and equipment, Worker, work assignments, authority structure, working environment, output	Microeconomic, Corporate
Mohsini and Davidson, 1991	1991	Journal	Yes	Descriptive Study	Industrial case studies	Procurement	Study of procurement decisions effect on design team performance	Clarity of scope of participation, sufficiency of information, rapidity of access to further information, degree of coordination of tasks, degree of specialisation, availability of further information, degree of task dependency	Corporate
Nath et al., 2015	2015	Journal	No	Empirical Study	Workflow analysis from value	Shop drawings producti	Identify constraints in present workflow and propose enhanced workflow	Queue/ wait time	Corporate
O'Donnell and Duffy, 2002	2002	Journal	No	Empirical Stud6	Design develomet	Design development mo	Analysis of performance at the project of program level	Completeness of information provided, design management	Microeconomic, Corporate
Plummer, 1956	1956	Journal	No	Descriptive Study	NA	Administration	Exploration of new techniques to increase engineer productivity through administrative planning and management	Personnel Policies, contract procedures, legislative support	Corporate, Microeconomic
Robinson et al., 2005	2005	Journal	No	Detailed Study	Three-phase quantitative and	All	Identification of future competency profile for design engineers	Personal attributes, project management, cognitive strategies, cognitive abilities, technical ability and communication	Individual
Rubin and Horstmann, 1983	1983	Conference	No	Empirical Study	Modelling, simulation and sta	Product Design	Analysis of developed design and verification IBM engineering design system	N.A.	
Sackett, 1989	1989	Conference	No	Empirical Study	Matrix formulation and analy	N.A.	Exploration of shift of studying engineering productivity to engineering effectiveness. Matrix tools for assessment and improvement of engineering effectiveness.	Project management, design control, process control, purchasing, CAD, technology utilisation, management style, culture and norms, communications, systems and procedures	Microeconomic, Corporate
Sacks and Barak, 2005	2005	Journal	No	Empirical Study	Review and analysis of engin	Construction stage	Examine the impact of shift towards 3D modelling in structural engineering design practices	N.A.	
Sacks and Barak, 2006	2006	Conference	No	Empirical Study	Economic analysis and mdel	All	Estimate the degree of productivity gain from 3D modelling and identify local process impacts and changes	Degree of drawing production activity	Corporate
Sacks and Barak, 2008	2008	Journal	No	Empirical Study	Economic analysis and mdel	Design documentation	Compilation of benchmark for structural engineering design and detailing Estimation of range of productivity gains expected from benchmarking	Degree of drawing production activity	Corporate
Saliminamin et al., 2019	2019	Journal	No	Detailed Study	IDEF0modelling, Experiment	Concept stage/ ideation	Performance analysis of R&D engineers in designing the next generation of a technical system	Design precedents, design strategies on idea generation, creative stimuli	Corporate
Schainblatt, 1982	1982	Journal	No	Review	N.A.	R&D	Review of productivity measurement of engineers and scientists	Probability of commercialisation, comprehensiveness of R&D Programme, Competitive technical status	Microeconomic
Song and AbouRizk, 2005	2005	Journal	No	Prescriptive Study	Case study application	Project planning	Propose quantitative engineering project scope definition to standardize measurement of project scope for further productivity applications	Poor project scope definition	Corporate
Thamhain, 1983	1983	Journal	No	Descriptive Study	Field study, questionnaire and	Engineering managemen	Professional needs expressed by engineering personnel analysed to achieve effective engineering performance	People skills, organisational structure, management style, surrounding environment	Corporate, Individual
Wang et al., 2010	2010	Conference	No	Descriptive Study	Early phase discovery and eva	System development pro	Proposed systems engineering productivity and efficiency measure	System size, system requirements, system interfaces, system-specific algorithms, operational scenarios	Microeconomic
Zanni et al., 2016	2016	Journal	Yes	Detailed Study	Abductive approach using cas	Early stages	Identify best practices in sustainable building design	Role, tasks and deliverables specification, repeatable detailed tasks, formal and informal communication in centralised system	Corporate

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4.2 Concurrent engineering

Another tool and concept to analyse design process models would be the application of the design structures matrix to manage concurrent engineering (Eppinger 1991). Applying concepts of concurrent engineering, one can identify iteration loops, and through rearranging design procedures, these loops can be decoupled, and the design process streamlined. Design structures matrix is also useful in other areas of analysis of design processes (see Section 2.5). It should be noted that concurrent engineering is also referred to as simultaneous engineering.

4.3 Design for X for conceptualisation

Design for X is closely tied to concurrent engineering; however, its application is especially important in the design concept stages. This is because the key concept stresses achieving objectives of concurrent engineering through co-operation between multiple disciplinary functions and to consider all interacting issues. (Eastman 2012).

4.4 Construction management

A systematic way to compare two editions of the RIBA plan of work was proposed where the analysis of the design process models employed construction management techniques instead of design research methods (Hughes 2003). The works by Hughes and his research team in construction management and engineering focus on analysing construction projects using different methods like organisational, risk, and procurement analysis. Some of his works also involve modelling construction projects using plans of work. Works in construction management are important to the understanding of AEC industry trends and needs so future research can benefit construction projects.

4.5 Information flow management

Studying the design processes in the AEC industry could also be performed solely through analysing information/data passed between stakeholders. This can be done through information flow modelling and is useful in the AEC industry as substantial volumes of information are produced circulated in construction projects. The design structures matrix mentioned in Section 2.2 was employed to model information flows in building design and used to explore the feasibility of design support that enables analysis of iterative information cycles(Pektaş and Pultar 2006). This process contributes to engineering productivity studies as iterative cycles are key indicators of design productivity.

5 PATTERNS IN LITERATURE

The analysis of the information was graphically summarised to identify patterns in the literature. A distinction is made between sources listed in Table 2- Focused group, and sources listed in a separate table containing the comprehensive group.

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5.1 Graphical summary of works

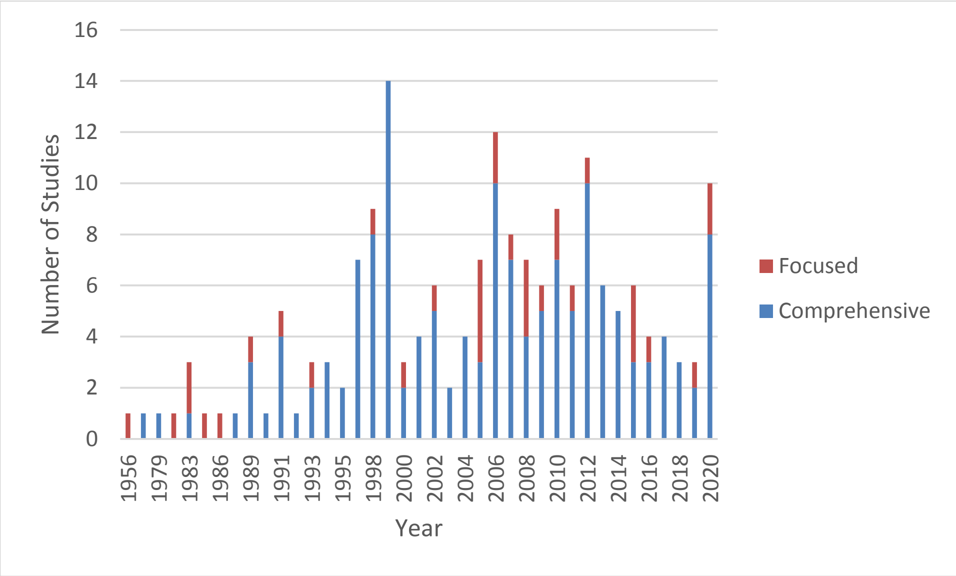

Figure 2. Number of selected engineering productivity studies by year of publication

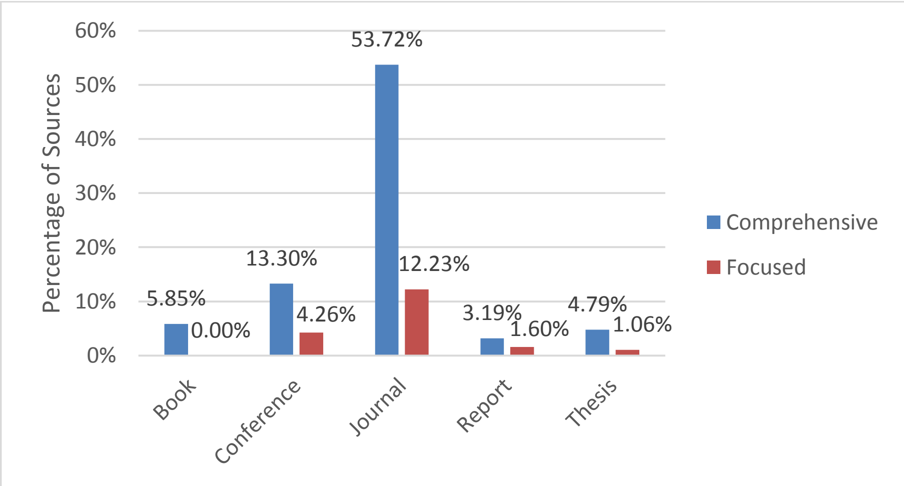

Figure 3. Distribution of publication sources

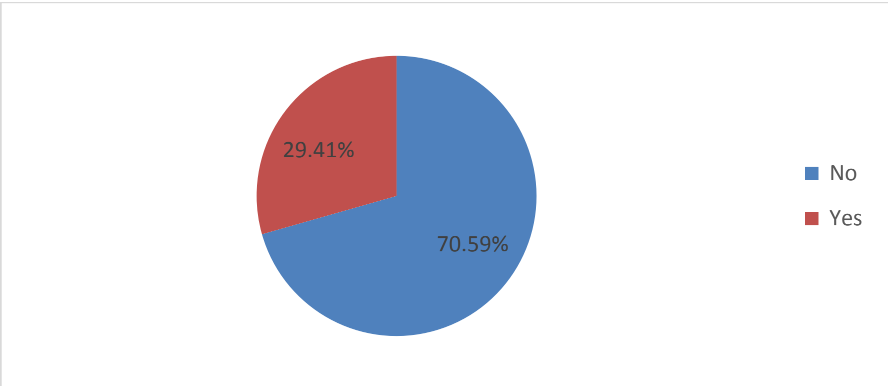

Figure 4. Proportion of studies including multi-stakeholder analysis

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6 DISCUSSION AND FUTURE RECOMMENDATIONS

No obvious trend was spotted in the number of publications in the field of engineering productivity in the AEC industry over the years. However, this study hypothesises that there could be have been increased research interest in this area following construction technology advances (like CAD and BIM technology) or the evolution of Industry 4.0.
The study analysed the degree to which multi-stakeholder and multi-disciplinary natures of the design process were included in the study of engineering productivity and did not observe a correlation in the resulting analysis. Nonetheless, due to the scope and limitations of the research, future work may wish to include it when performing engineering productivity studies in the AEC industry.
The degree of an engineer's/ designer's phase involvement specifically in the conceptual design stage is potentially significant towards engineering productivity, however, results from this study cannot support this conclusion.
Engineering productivity studies are highly reliant on industry support for data, however, this was not reflected in the sources of publications, which are mainly journal articles. Further work could analyse the sources of funding and data behind most of the work published through academic journals.

7 CONCLUSION

Although the analysis of the systematic literature review is not coherent to the first author's anecdotal evidence, the paper presents the extracted factors influencing engineering productivity in the AEC industry. Through the review, the author further identified key topics and concepts within the design research field that apply to engineering productivity studies.
Most importantly, design research methods are not widely employed in the study of engineering productivity in the AEC industry despite being applied to other fields of engineering. However, increasing interests in this area show the potentials of applying such methods to streamline design workflows and processes realised through the study of engineer productivity.
As the AEC industry faces more stringent challenges, with an increased need for designs to perform efficiently and economically, engineering productivity studies will be crucial to a comprehensive productivity study of the whole industry.

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