Comparator Mechanism Team Report

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Executive summary

This report was peppered as part of the CanConstruct research programme. The aim of the report is to understand the information gathered and facilitate pipeline and sector comparison. In addition, the report will include an initial concept model for comparing pipeline and sector information. The methodology consists of Phase 1-Exploring, understanding and simplification; Phase 2-Classification of identifiers; and Phase 3-Concept comparator development. As part of phase one, Facilitated Modelling Workshops and four comparative case studies were conducted, and a common information framework was proposed. Data structure and availability was tested through a relational modelling step. As a result, simplification assumptions were suggested by CanConstruct leadership team. This was done to enable a comparison of pipeline and sector information. The initial comparator mechanism was developed based on the available MoE data for Auckland region. The comparator was developed via Power BI software and application of power quarry functions. Furthermore, Agent Based Modeling was used as a more sophisticated modelling technique. Both methods demonstrated a lack of capacity for the sector to meet the demand of future work. Although there were limitations with data availability and accuracy issues due to simplification assumption; this report has demonstrated a proof of concept for the comparator mechanism, and as a result, reliable and practical outputs have been generated.

Introduction

Access to reliable prediction and clear understanding of the demand and supply is essential for major clients, government agencies, contractors and other stakeholders involved in construction activities (Wong et al., 2010). However, the construction industry traditionally has faced many uncertainties and issues at different levels of planning including supply and demand assessment. This is partly due to the temporary, project based and complex nature of construction activities. Furthermore, the pipeline of work follows cyclic boom-bust trends, and this is a global phenomenon with economic and political underpinnings (in 't Veld et al., 2014). Generally, construction pipeline assessment and estimations are very high-level, nonstandard and to some degree superficial. These assessments lack reliable and valid input data, and accordingly a robust method of analysis (Wong et al., 2010).

In addition, the construction sector and business environment are constantly changing due to its dynamic exchanges with other industries (Too, 2012). The sector constantly is dealing with shortage of skilled professionals, trades, and is in competition with other sectors over unskilled workers (Oke et al., 2018). This has detrimental effects on New Zealand construction and infrastructure project delivery (Lobo & Wilkinson, 2008). Adding to these issues are the occurrence of major disruptive events such as the current global pandemic, earthquakes, supply chain problems and even technological change with significant impact on construction demand and supply (Chang-Richards et al., 2017). New Zealand construction industry also lacks systematic and standard record keeping and application of information systems are not very sophisticated within the sector (Eliwa et al., 2022). The data sources are often outdated, inconsistent, and of poor quality which adds another level of complexity for any meaningful evaluation of the sector capacity and capability to meet industry demand.

Therefore, the aim of this report is to understand the information gathered (by other CanConstructNZ teams) and facilitate pipeline and sector comparison. Recommendations will be provided on use of appropriate platforms, tools, and processes for data management and aggregation. The report will include an initial concept model for comparing pipeline and sector information. Further modelling methods and inference mechanisms are suggested for moving beyond the simplicity of the current case study assumptions. This is part of the long-term goal of CanConstructNZ research programme to assess and enhance Capacity and Capability for the New Zealand Construction Sector.

Background

In order to assess and evaluate capacity and capability common identifiers relating to the demand and supply dyad are required. Pipeline is often are an indication of upcoming projects (demand) and is a common concept in construction and infrastructure planning and investment discussions (Moradi et al., 2019; Zhu et al., 2021). On the other hand, the construction sector generally responds to the demand by providing resources and skills. Sector is often classified as vertical or horizontal by the nature of the work and normally is defined by the stakeholders who are involved in either or both of vertical or horizontal work (Lee & Shin, 2017). These stakeholders could be contractors, designers, consultants, sub-contractors, skilled trades, suppliers, etc.

Other considerations are the disruption caused to the demand-supply dyad; which include shocks and stresses such as the current global pandemic, disaster events such as earthquakes, floods, tsunamis, etc. Shocks and stresses can affect both pipeline and sector; triggering various demand-supply disruptions. Resilience as the ability of an organization or a systems to cope and adapts with these disruptive effects with minimal damages and destruction, also needs to be assessed (Ekanayake et al., 2021).

One of the major challenges of the current programme is unviability of good quality data. Often with available datasets there are major inconsistencies and large number of missing values. The other major challenge for the programme is complexity of concepts and creating a shared understanding amongst the research teams involved. This is essential in creating the basis of comparison for pipeline and sector information. The simplification requires understanding of cases were pipeline and sector data are available; facilitating, classification of practical and measurable identifiers and enabling a meaningful comparison of the demand and supply.

Methodology

The methodology to achieve report objective consist of three distinct phases, illustrated in Figure 1. Respectively, these phases are Phase 1-Exploring, understanding and simplification; Phase 2-Classification of identifiers; and Phase 3-Concept comparator development. These phases cover five different steps of mixed qualitative and quantitate research approach (see Figure 1). The challenge in this study is the complex, multidimensional and unstructured nature of the concepts explored. The mixed research approach is popular in construction research particularly in dealing with unstructured knowledge areas (Babaeian Jelodar *et al.*, 2021; Schmidt *et al.*, 2017).

Step1-Facilitated Modelling Workshops

Facilitated Modelling Workshops (FMW) are extremely effective with problems of multidisciplinary nature which involve significant levels of complexity (Franco & Rouwette, 2011). It allows for cross examination of the problem from different perspectives and allows for cross-functional teams involvement (Franco & Montibeller, 2010). Workshop participants were CanConstructNZ team leaders and members who have knowledge and decision-making authority for the next stages of the investigation. CanConstructNZ programme consists of five teams which lead different aspects of the programme (Appendix A). The FMW workshops were held with representation from all five teams involved in CanConstructNZ. The conceptualisation and outcomes of these workshops are included in Appendix B to F. As demonstrated in Figure 1 the progressive FMW spanned over the three phases of the study. Feedback loops were created to link the outcomes of the next steps as inputs for the progressive FMW sessions at each phase of the study. Accordingly, the analysed outputs of FMW were inputted in the next steps of the methodology.

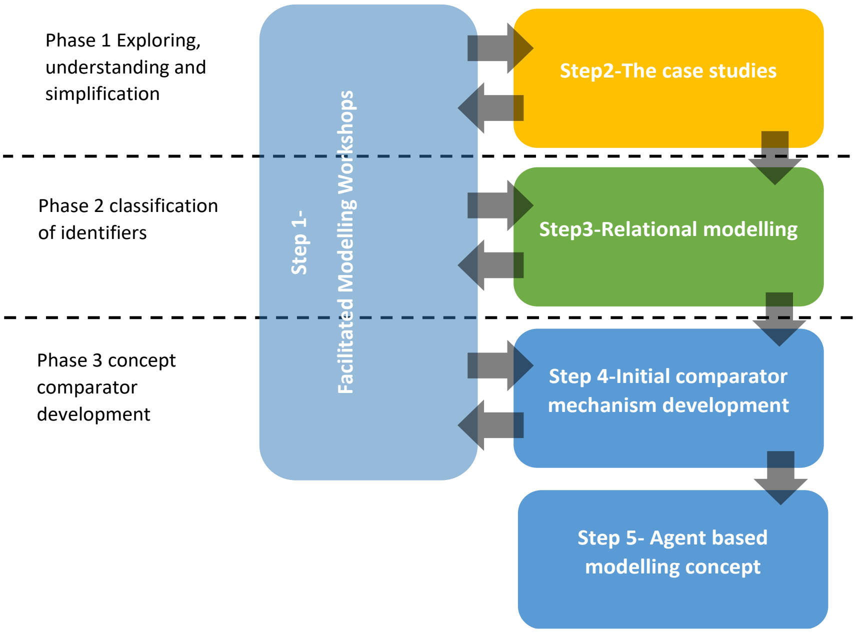

Figure 1 The research framework

Step2-The case studies

In order to explore possible identifiers, creating a shared understanding and simplification of pipeline and sector information a comparative case study approach was adopted in phase one of the study (Babaeian Jelodar et al., 2021; Dansoh et al., 2017; Yin, 2017). Four cases are selected to represent the New Zealand construction industry. The aim was to capture different authorising and client organisations with diversity of projects, representation of both the horizonal and vertical sectors and inclusion of different levels of construction work complexity. The following four cases were chosen:

- New Zealand Ministry of education (MoE) construction work
- New Zealand Transport Agency (NZTA) - Waka Kotahi; construction work
- Palmerston North City Council construction work
- The Dunedin Hospital project

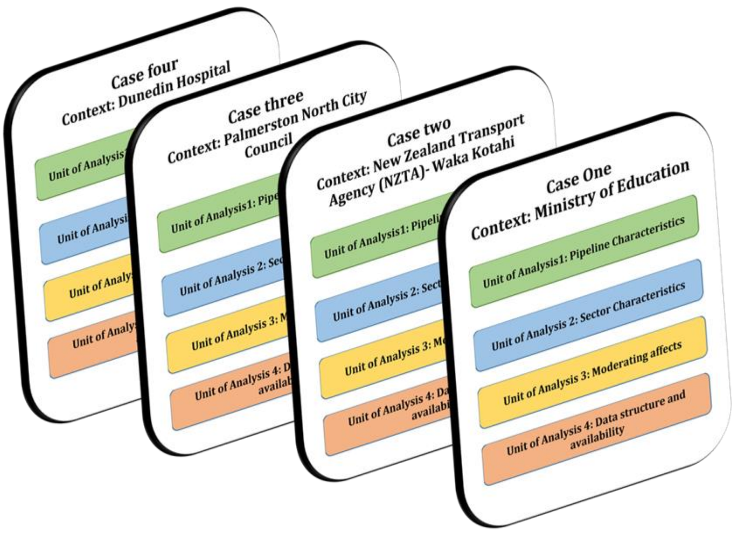

Figure 2 Case study framework

The case study methodology will provide specific details on pipeline information captured for different scenarios (Yin, 2017). In order to make a valid comprehensive comparison and evaluation a case study framework is designed to explore the features of the four cases (see Figure 2). The case study framework includes the context of each case plus four units of analysis, which makes the comparison of the cases possible (Fellows & Liu, 1997; Yin, 2017). The case study characteristics are discussed in FMW sessions, and four units of analysis are derived for this study. The unites of analysis include pipeline characteristics, sector characteristics, moderating effects and data structure and availability.

Step3-Relational modelling - Relational Database Management System (RDBMS)

The information and data obtained from the previous two steps are collated discussed in the FMW sessions. Accordingly, the obtained information and data are classified and structured via development of a Relational Database Management System (RDBMS). The aim is to scrutinise the information and data structures obtained from previous steps. This allows to categorize and evaluate potential identifiers within pipeline and sector information and identify potential shortcomings of the database. RDBMS is a type of database management system that stores the data based on the structure and connects them based on the related data elements (Sobhkhiz et al., 2021). RDBMS supports a relational model and maps the relationships between data elements. This relational model uses the key concepts (primary keys) to connect the norm tables (Fernández & Varga, 2020). In this study, based on the FMW and case studies conducted common identifiers are categorised and a database is created to capture these identifiers. Data then is normalized in a systematic approach to add more structure to the database. Normalization is a process of restructuring and rearranging the data in the database based on the observed and classified identifiers to minimize redundancy (Albarak et al., 2020).

Step 4-Initial comparator mechanism development

At the time of the study the most complete dataset available was the MoE for Auckland region. After rigorous screening the missing values were estimated, and the dataset was standardised. Based on information obtained from previous phases simplification assumptions were proposed by CanConstructNZ leadership team. These assumptions form the basis of the comparator mechanism.

Microsoft Power BI software is used for data analysis and visualisation in this study (Sousa et al., 2021). Power BI is a business intelligence tool deployed in national and international enterprises, enabling organisations to enhance data management efficiency and data driven decisions (Kajava, 2018). Power BI is an ideal platform because it integrates easily with other tools such as Excel and SQL, webpages, text and PDF. Power BI has the following essential capability necessary to the comparator mechanism:

- The contemporary interactive visualisation
- Unlimited access to local and cloud data
- Creating a real-time dashboard to aid decision making
- Secure data sharing
- Easy to filter the data

The dashboard in Figure 3 was developed via Power BI. The develop dashboard facilitates comparison of pipeline information against the sector information with the ability to customise information. To simplify and enable connectivity and data transfer from source databases a power query function is employed. Power Query allows users to seamlessly access data stored in other sources while changing it to meet specific needs. Power Query Editor is included with Power BI Desktop and designed for the complex datasets. It can also carry a code for consistency and data ordering without changing the original data source (Harode et al., 2022; Kajava, 2018).

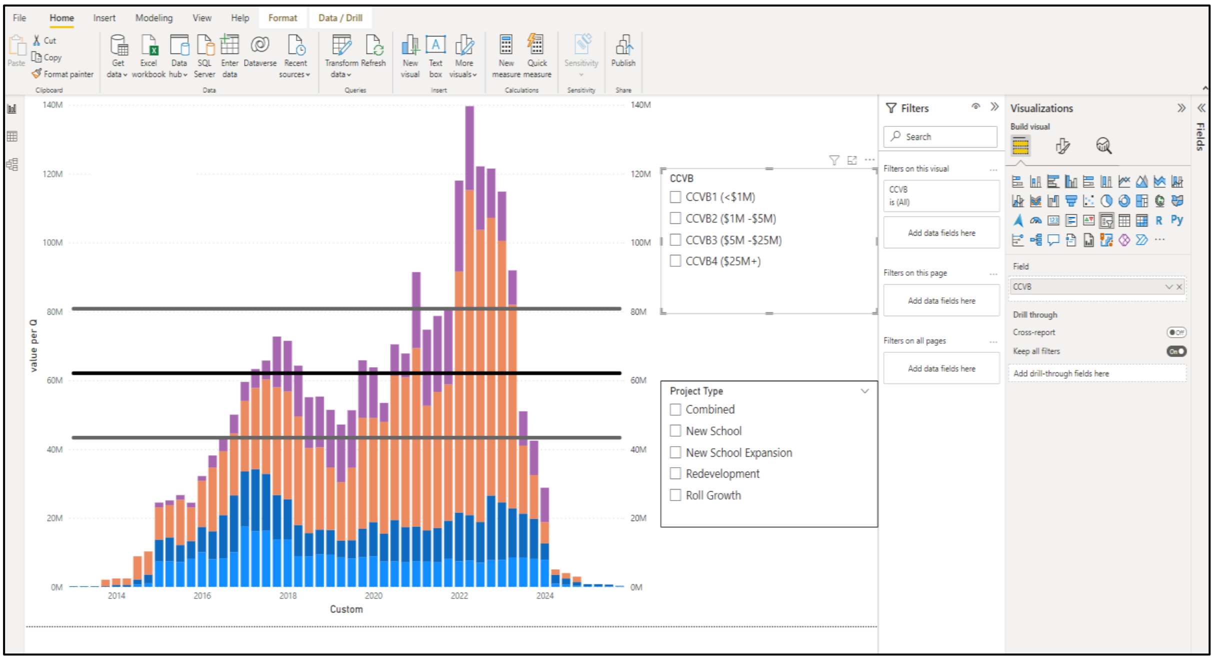

Figure 3 Power BI Platform

Step 5- agent based modelling concept

To provide a realistic method of simulating and modelling pipeline and sector information multi-project portfolio (MPP) management theories can be applied; where multiple projects in the pipeline all consume from resource provided from the sector. Multi-project portfolio (MPP) is often applied for budget allocation, prioritisation and proper timing of a portfolio of projects (Farshchian & Heravi, 2018). Agent-based modelling (ABM), as a dynamic modelling approach is widespread for modelling, simulating, predicting, and taking a step forward toward understanding such complexities and uncertainties (Farshchian et al., 2017; Hans et al., 2007). ABM typically includes two important components called agents and environment. These entities are artificial entities (sub-systems) that mimic real-world attributes, behaviour and interactions. ABM is useful for understanding the collective behaviour of multitudes (agents) in a context (environment and applied rules for interactions)(Younes & Marzouk, 2018). For this study the projects in the pipeline are considered as agents and the sector information and limitations defines the environment for these agents. For a comprehensive literature review see the paper submitted to EPPM2022 (Appendix L). Based on the ABM requirements and simplification assumption developed through FMW a data structure was created and a final request of information was sent to all CanConstructNZ team leaders. See appendix M for the Python code developed and request for information. The initial model concept was created via Grasshopper visual programming language.

Results

Results for the FMW

The FMW were conducted over 9 different sessions as the study progressed; and accordingly, data and information became available. A total of 12 participants took part in these facilitated workshop sessions, which included team leaders and representatives from the five CanConstructNZ research teams. The workshops were based on consultancy engagement models via an objective analysis of the problem (Franco & Montibeller, 2010). Table 1 includes descriptions, inputs and outputs of each session; and each row of the table demonstrates one workshop session.

Table 1 Summary of the facilitated modelling sessions

Phase	Workshops themes	Description	Inputs	Outputs
Phase 1 Exploring, understanding and simplification	**Framing and capturing the problem**	The focus was mainly on capacity and capability indictors. The goal was also to discuss different case study consideration and provide a high-level structure of information required.	Previous literature on capacity and capability. available industry reports Brief description of the each of the four cases was provided by case study leaders.	Agreed Main Capacity Indicators for the construction sector (Discussions were based on available literature, existing findings, and professional expertise). Initial case study consideration and information classification **(Appendix B)**
	Initial problem formulation	At this session the aim was to assess and evaluate the four cases; and discuss how capacity and capability indicators could be conceptualised The issue of resilience indicators was discussed The focus was on concept model considerations	Agreed capacity indicators Each case study initial assessment and characteristic Some potential shocks and stresses as demand and supply disruptors were discussed	Introduction of shocks and stresses as potential moderating affects to the concept model Initial request for information was sent to case studies leaders. **(Appendix C)**
	Defining metrics	The first data sources available were discussed and their structure was scrutinised (mainly based on MoE information). Based on what was available and what is required different metrics were identified.	Data sources and structures identified this included: • Structure datasets • Totally unstructured information in different formats.	Initial case study metrics were identified; based on this a more detailed request for information was developed and communicated to team leaders **(Appendix D)**
	Data collection strategies	The intent was to develop a strategy to collect as much relevant and comprehensive data as possible. Extensive debate took place on the value and criticality of historical information.	The data sources available. Team provided an initial brief on case study progression.	A data collection strategy example was created; this was based on the available MoE information. However, this was applicable to the other cases too. The document was shred to all team leaders, which also included some highlighted actions. **(Appendix E)**
Phase 2 classification of identifiers	**Evaluating data and options**	The focus was on collating and linking different data sources. Inclusion and exclusion criteria for the information. The need for historical data for model development was emphasised- this will be used post concept model development.	Pipeline and sector information collected from MoE case. Relational modelling literature.	Process of relational modelling, links between indicators in available datasets were established. A request for Historical information was sent **(Appendix F)**
	Preparing results	Discussion on pipeline and sector characteristics were conducted. The focus was on identifying unique feature and similarities between the cases.	Latest MoE information. Initial NZTA was discussed, this was only for one region.	Comparative case study analysis for unique features of the cases **(Appendix G and H)** Development of common information framework for the case studies.
Phase 3 concept comparator development	**Simplification assumptions**	Assumptions were proposed by CanConstructNZ Leadership;	The second revision report submitted by CanConstructNZ teams.	Simplified pipeline and sector assumption with the aim of providing practical model identifiers.
	Initial model concept	To have a meaningful comparison of pipeline and sector. Platform and modelling methods application.	Comparative analysis of the available information from previses stage. Data structure and availability **(Appendix H)**	Assumptions for Initial model concept development.

The first column in Table 1 demonstrates the research phase and the second column includes the themes of the facilitated workshops. The FMW allowed for planning and decision making based on actual inputs-outputs feedback loops; enabled achievement of shared understanding; led to development of data collection strategies for case studies; enhanced agreements on of identifiers amongst other things.

Results for Case studies

Based on a comparative analysis of the four cases; unique and common features of these cases are identified and discussed. The analysis also identified high-level sector and pipeline identifiers, relationships, data sources and moderating effects which will serve as inputs to the concept model development. The case studies are performed based on assessments, outputs and strategies developed in the previous facilitated workshop stage. The detailed analysis of the cases is provided in Appendix G, H and I. In this section a brief description of the four cases are provided (see Table 2).

Table 2 Basic model elements – full information available in Appendix G

Case Study	Pipeline characteristics	Sector characteristics	Moderating affects	Data structure and availability
Ministry of Education	**Value band** -5 value bands (under0.5M till 20 M+) **Locations** -Whole NZ (10 regions) **Project types** -Combined -Learning Support - Modification -LSPM -New School -New School Expansion -Redevelopment -Roll Growth **Priority** -(High / Medium / Low) -(Medium / Low) **Project Phase** -16 phases	Mainly vertical **Prequalification based on project type** -yes **Sector Stakeholders** -QuantitySurveyor -ProjectManager -MasterPlanner -LeadDesigner -Contractors **The supply chain information** -Not specified	-Economic resilience -Built Environment -Natural environment -Social -Governance of risk	**Structured and unstructured data** -Annual reports -Website -Interview
Waka Kotahi NZ Transport Agency	**Value band** -Actual/estimated value **Locations:** -Whole NZ -6 regions nationally **Phase type:** -10 Activities **Priority:** -1 to 12 **Funding source:** -5 sources	Mainly horizontal **Prequalification based on project type** -yes **Stakeholders** -Contractors **The supply chain information** -Not specified	-Economic resilience -Built Environment -Natural environment -Social -Governance of risk	**Structured and unstructured data** -Annual reports -Website -Interview **Region of operations are available; only the following regions:** -Gisborne -Hawkes Bay -Manawatu/Whanganui Taranaki
Palmerston North City Council	**Value band** 9 value bands (Under 1M till 1 B+) **Location:** 1 region (Manawatu – Whanganui) **Procurement method**	Mix of vertical and horizontal **Prequalification based on project type** -Not specified **Stakeholders** -Not specified **The supply chain information** -Not specified	-Economic resilience -Built Environment -Natural environment -Social -Governance of risk	**Structured and unstructured data** -Annual reports -Website -Interview - Ref:Infracom Data - Pipeline-Data-14-02-22-Public-Version
Dunedin Hospital	**Value band** -Actual value **Approved budget** -In 3 different phases **Location** -1 region	Vertical **Prequalification based on project type** -Not specified **Stakeholders** -Not specified **The supply chain information** -yes	-Economic resilience -Built Environment -Natural environment -Social -Governance of risk	-Structured and unstructured data -Annual reports -Website -Interview

The cross-sectional case examinations have demonstrated some unique features of each case study; and suggest that apart form fundamentally different characteristics, the data structure and availability is also extremely variable from one case to another. However, based on the unites of analysis used in the case studies a common indicator for pipeline and sector information can be proposed as the bases of any compression. As demonstrated in the previous section and although it is far from ideal, the MoE case has the most comprehensive profile of pipeline information. Their sector information in most cases are just lists of contractors who are prequalified or eligible to perform the projects. Currently there are substantial amount of missing and incomplete information. This demonstrates that record keeping, and construction databases are very inconsistent and of poor quality (see Figure 4).

	Common information required for each case
Pipeline information	• Project type • Location • Value • Duration (Start and End Date) • Priority based on project type
Sector informati on	• Vertical vs Horizontal • Prequalification based on project type • Stakeholders (i.e. Contractors tiers…) • Supply chain based on project type
Moderating effects (i.e. resilience factors)	• Shocks • Stresses • Market forces (major industry player: i.e. Tier one contractors, major infrastructure projects, etc.)
Data	• Data structure • Availability of data

Figure 4 common information framework

Results of Relational modelling

Based on the common information framework and Relational Database Management System (RDBMS) in Power BI a decision tree was mapped to accumulate project value over time (Figure 5).

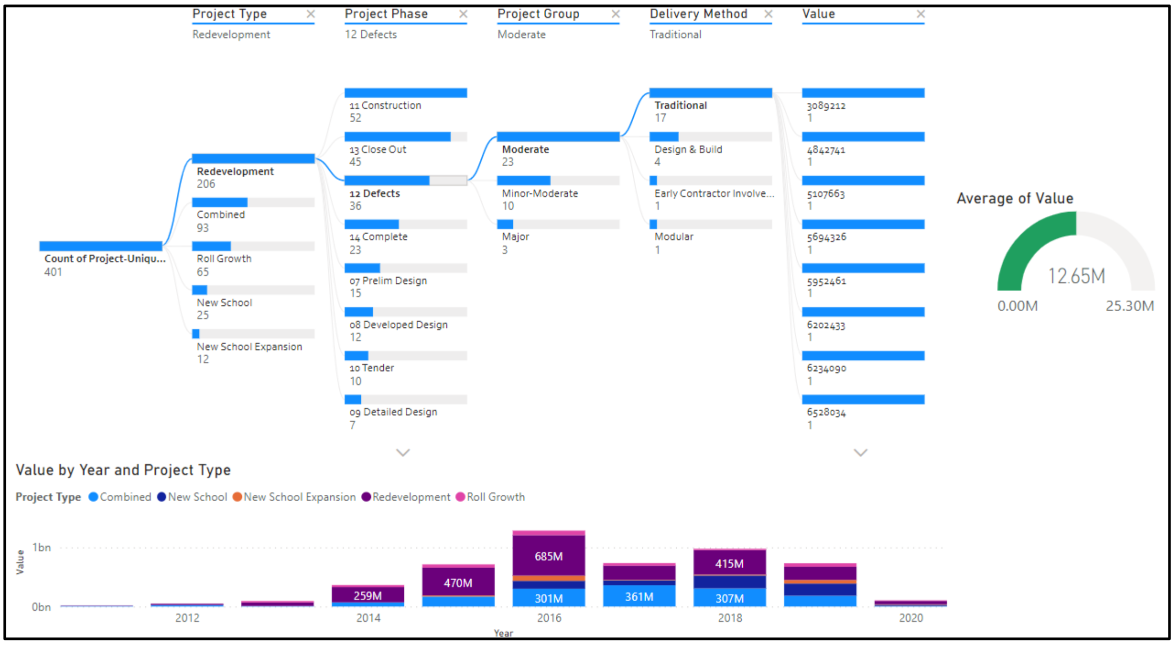

Figure 5 A real-time decision-making artificial intelligence (AI) visualisation – MoE case study

Accordingly, data project value was distributed over project duration. Different colour shows different type of projects. The second chart shows the annual duration of each phase (see Figure 6).

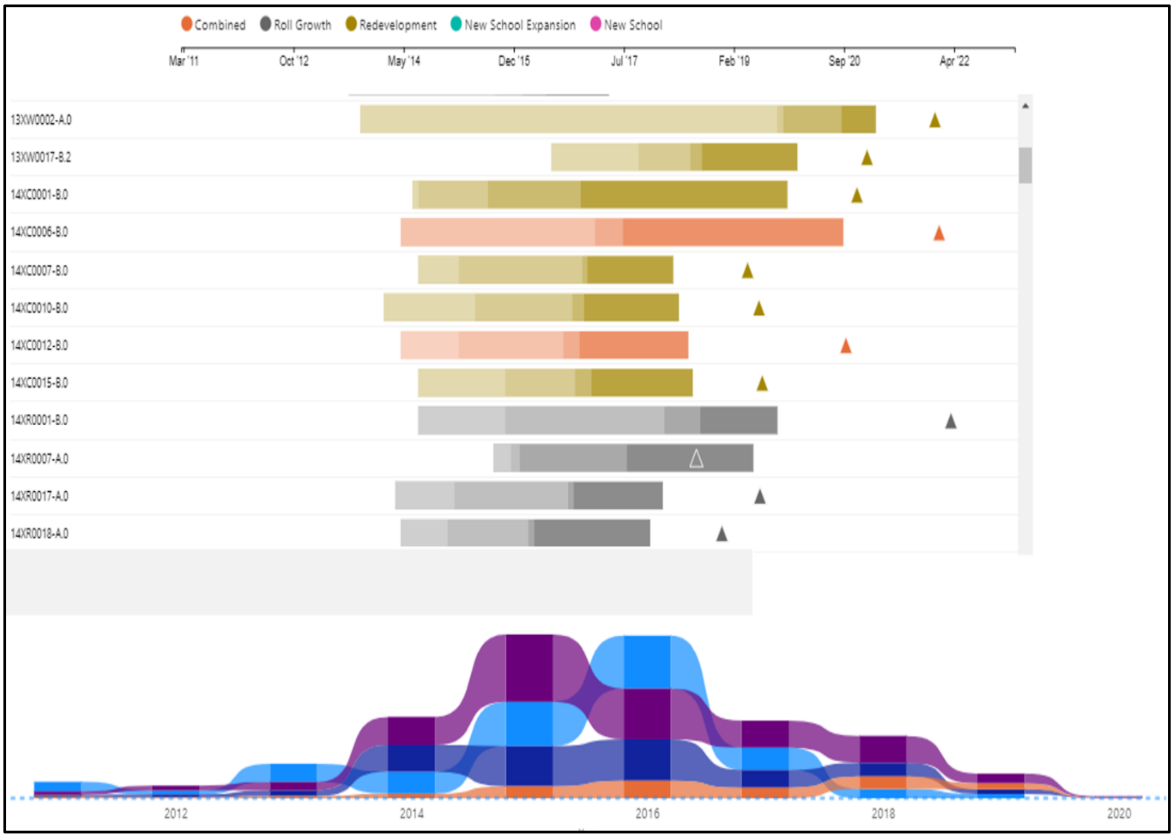

Figure 6 projects value distribution based on time and project type- MoE actual data

However due to missing values and over complications of data structure pipeline project values were under represented and the estimation of sector size was extremely complex. This reinforced the need for comprehensive and simplified assumptions for pipeline and sector evaluation. Accordingly, after further considerations, the evaluation of the outputs and data structure the simplified assumptions were provided by the CanConstructNZ leadership team and used in the next step of the study.

Results of initial comparator mechanism development

At the time of the study the most complete dataset available was the MoE data for Auckland region. After rigorous screening the missing values were estimated, and the dataset was standardised based on CanConstructNZ simplification assumptions. Microsoft Power BI is used as a platform for data visualization and analysis. An estimated capacity of different tier contractors was provided by the sector team. The estimates were provided for work done at national level. Further assumptions were made to estimate capacity of the different contractor tiers for Auckland Area. The annual growth rate is assumed zero for this stage of the study (see Table 3).

Figure 7 demonstrates the estimated total turnover of each tier contractors. This is an indication of work secured by these contractors and the work is also sub-contracted to other lower tier contractors. The turnovers are also broken down based on the CanConstructNZ assumptions for sector capacity and sub-contracting. For instance, 60% of the 95 million dollars turnover associated to tier 1 contractors are assumed to be sub-contracted to tier 2. Accordingly, Figure 8 demonstrates the estimate of annual turnover after applying subcontractor assumptions which is organising based on highest value. Value of work done by tier two (work distributed to tier 2) contractors is the highest, and even tier 3 contractors perform more actual work than tier one contractors.

Table 3 Auckland region contractors estimate of turnover

Contactor type	Annual turnover	Quarterly turnover	Assumptions for Auckland region capacity
Tier 1	95M	23.75M	10% of the work is done for MoE 43% of the work is done in NNI (Historic) 80% of the work in NN is associated with Auckland
Tier 2	55M	13.75M	20% of the work is done for MoE 43% of the work is done in NNI (Historic) 80% of the work in NN is associated with Auckland
Tier 3	66M	16.5M	30% of the work is done for MoE Only in NNI (No Mobility within regions) 80% of the work in NN is associated with Auckland
Tier 4	32M	8M	40% of the work is done for MoE Only in NNI (No Mobility within regions) 80% of the work in NN is associated with Auckland
Total	248M	62M	Indictor for Capacity (see black horizontal line Figure 9)

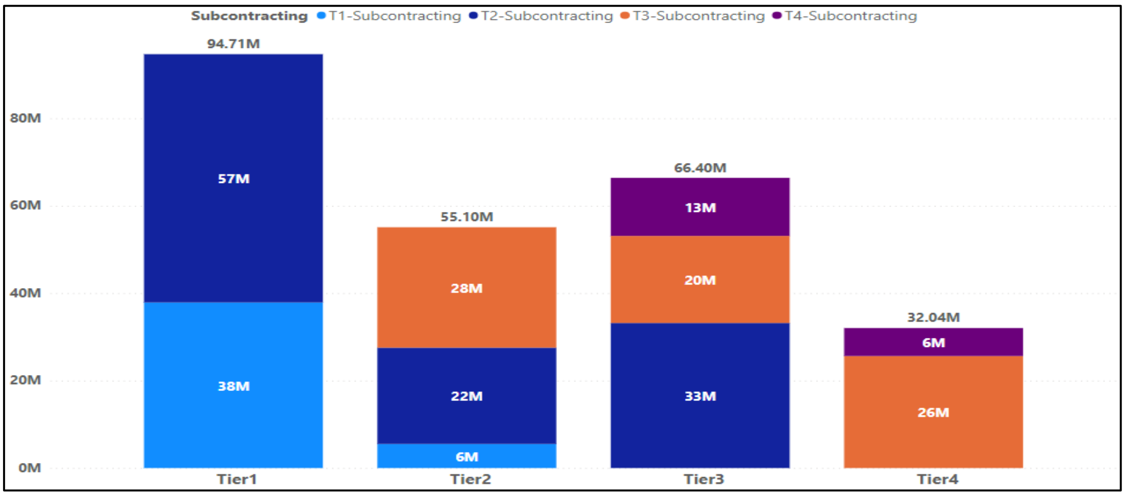

Figure 7 MoE contractor turnover for Auckland region (Wok secured)

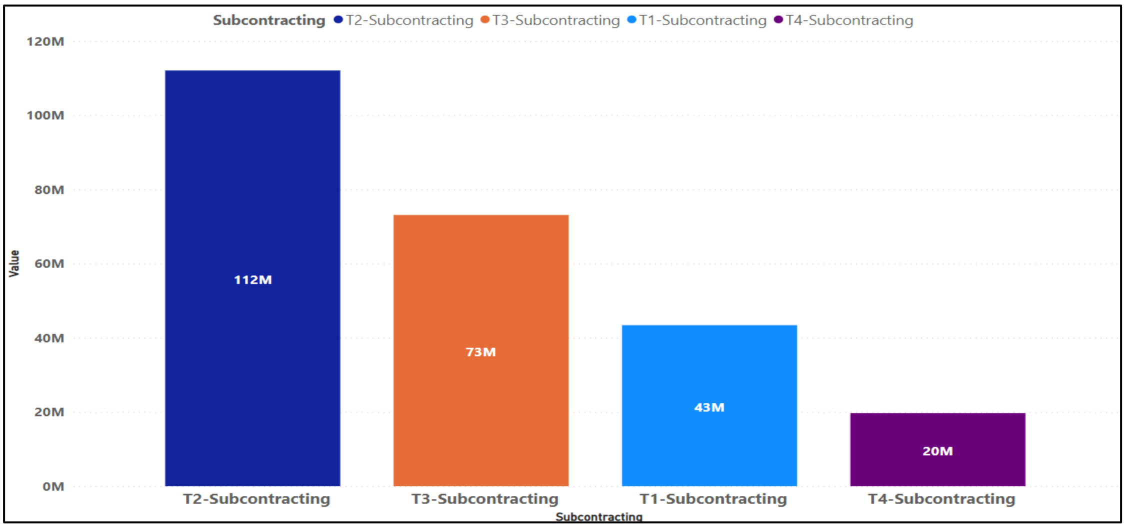

Figure 8 MoE turnover for Auckland region contractors after applying sub-contracting assumptions (Work distributed)

The standardised and normalised quarterly value distribution based on existing MoE pipeline database is demonstrated via the columns in Figure 9. The columns are also divided based on the four CanConstructNZ standard value bands. This is an indication of work performed at Auckland region during the period that project/pipeline data was available.

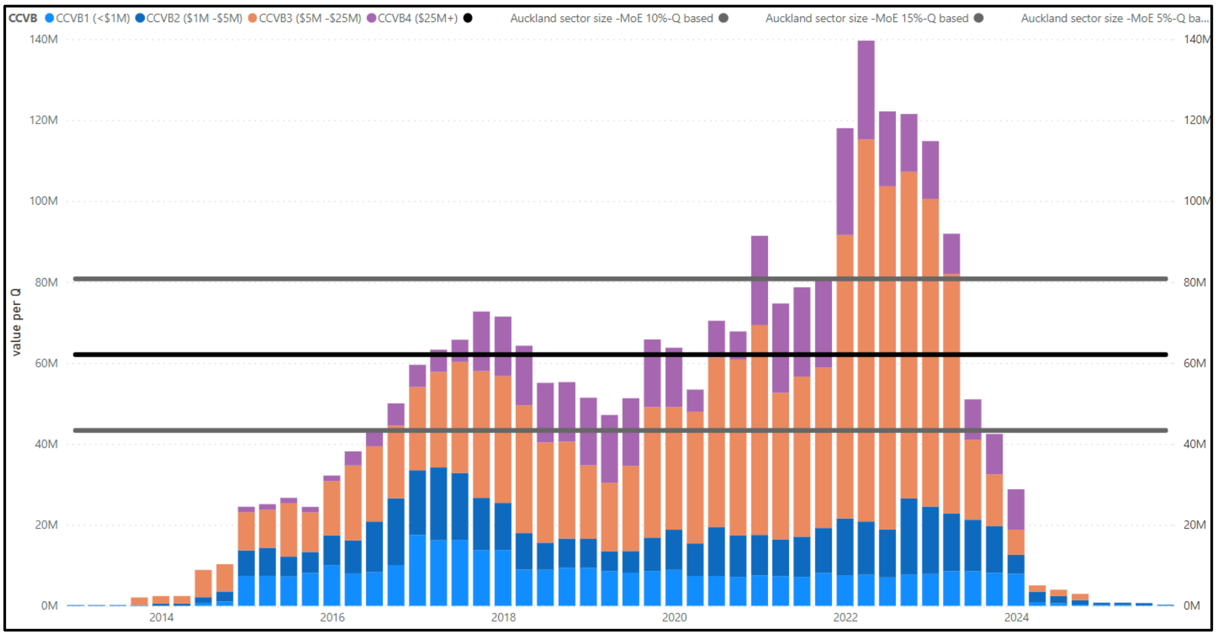

Figure 9 Pipeline and sector comparison

The black horizontal line is plotted based on total quarterly turnover estimate (Table 3) and represent sector capacity at zero percent annual growth rate. The grey lines provide a range for the Auckland sector based on the assumption of ±5% variations to tier 1 and 2 capacity. As evident the quarterly value of work has a growing trend which the sector capacity estimation based on CanConstructNZ assumptions.

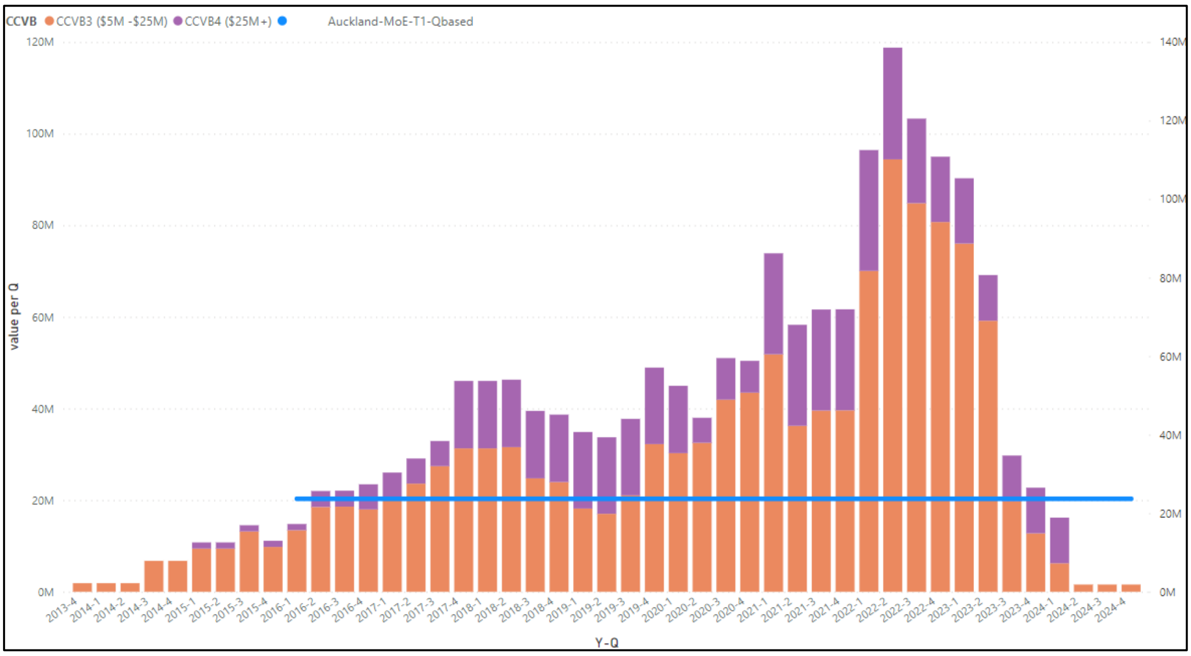

Figure 10 MoE Pipeline projects for value band 3 and 4 Vs. Auckland T1 capacity

Figures 10, and 11 demonstrates total quarterly value of Auckland region pipeline projects in CanConstructNZ value band $5M-$25M and above $25M are compared with the Capacity of the Tier1 and Tier 2 companies in the Auckland sector. It is assumed that only tier 1 and 2 contractors will be able to work on the projects within these value bands.

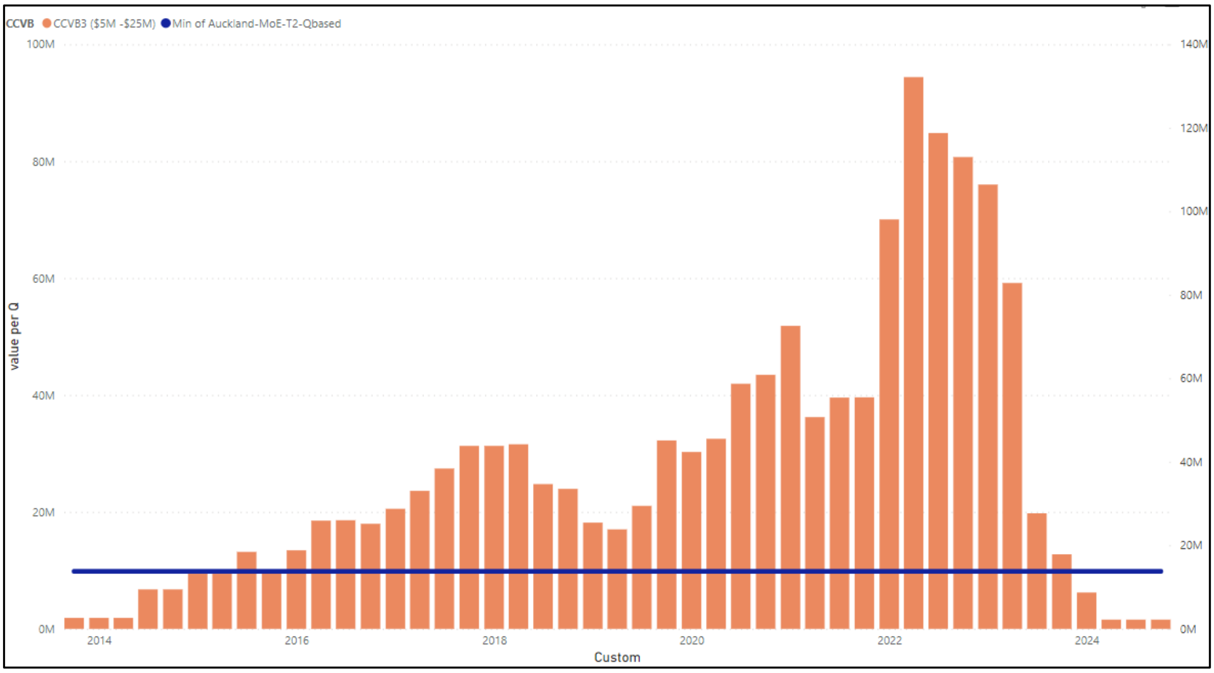

Figure 11 MoE Pipeline projects for value band 3 Vs. Auckland T2 capacity

Finally, via the application of time series analysis the future trends of the pipeline of work for Auckland region is estimated for the next three years and compared against sector capacity estimate (see Figure 12). A three-year period is chosen because most government agencies have three-year plans for their pipeline of work (Palma-Ruiz et al., 2022).

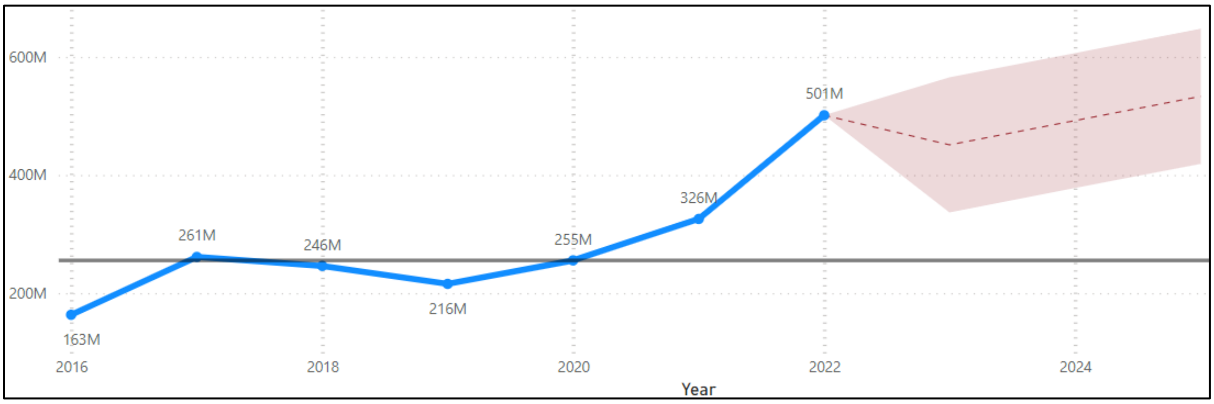

Figure 12 Three-year MoE pipeline trend estimate for Auckland region Vs sector capacity estimate

Results of Agent Based Modelling (ABM) concept

The ABM model was developed based on MoE Auckland pipeline information. Grasshopper (plugin for Rhinoceros software) canvas; visual programming and data visualization tool was used (Appendix M). Similar to the previous section the sector capacity assumptions are based on the four CanConstructNZ tiers and provided by the sector team. The ABM modeling was performed based on the annual turnovers estimated in Table 3; with the annual growth rate is assumed zero for this stage of the study.

Figure 13 illustrates the projects distributed yearly with corresponding distributed values as circles (Diameter=distributed value). The colors and unique IDs are employed as Unicode for the projects. The projects are located from left to right, based on priority level where the initial configuration was based on random propagation. Defining the priority level, it is assumed that the projects with earlier starting time should be continued for the succeeding years, thus, to be closer located at the left side. In other words, for time t, the projects that have been started at time t-1 or earlier are prioritized (the earlier the start date, the more prior the project). The model allows tracking of projects over time based on UniCode and colour assigned (Figure 14).

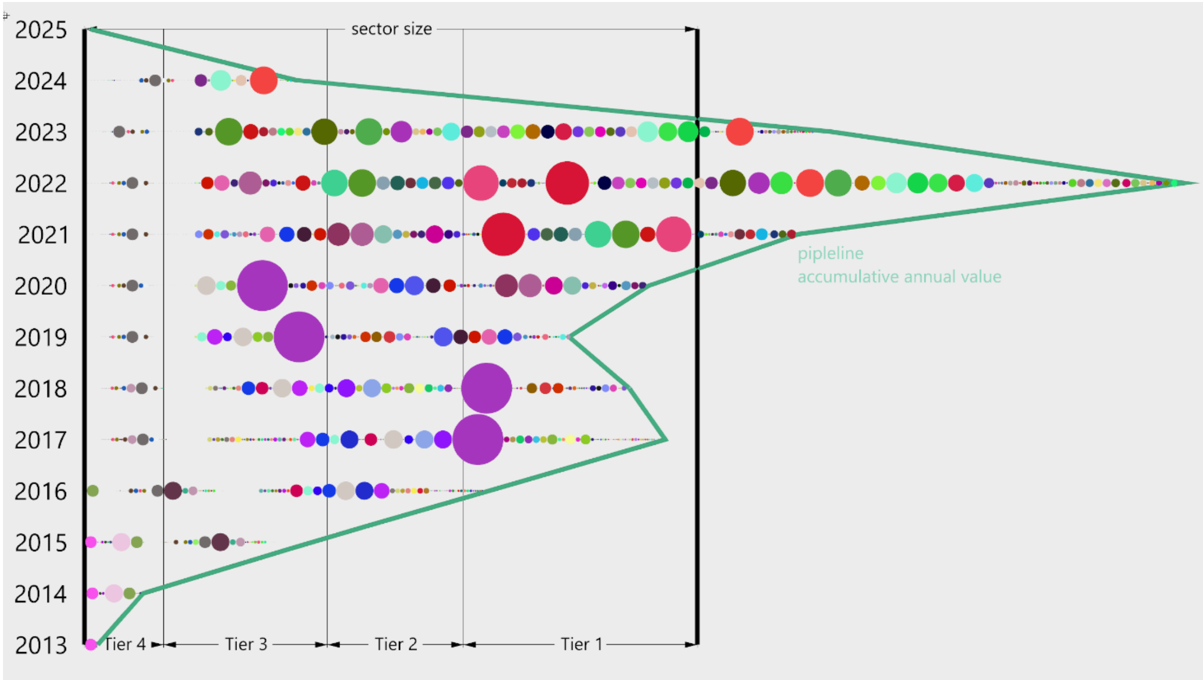

Figure 13 project value and tracking in ABM based on MoE data for Auckland region

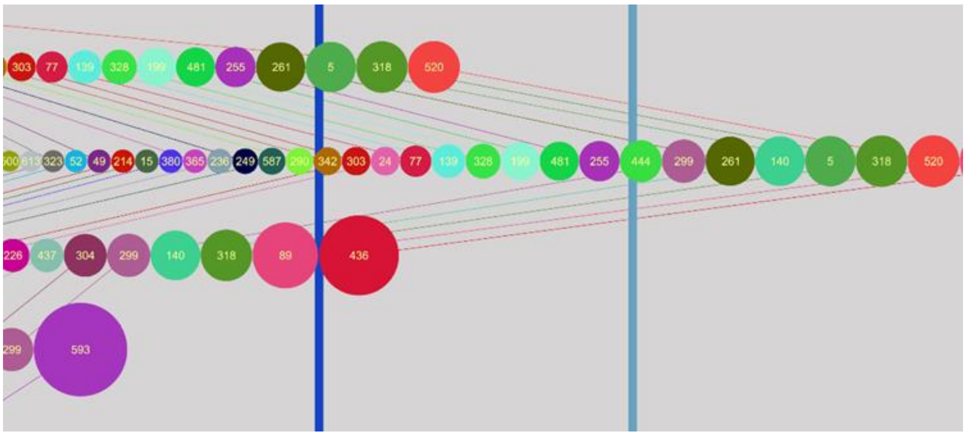

Figure 14 Close-up of project tracking over time.

This creates a visual for all the projects in the pipeline and understanding of their relative size. Figure 13 denotes the sector size divided based on each contractor's (in Tiers) capacity. The challenge here is to locate the projects (all the distributed parts of a single project) within the appropriate contractor tier portfolio. For example, in Figure 15 the project with the unique id No.593 (duration=4years) is located in the capacity reserved for Tier 1 contractors for the two first years of its life time, while the last two years are taken by the Tier 3 contractors. This seems to be rational with the assumption that as project progresses more of it will be sub-contracted. However, the actual distribution of work to the sub-contractors is unresolved. Also, it is aimed to solve this problem with considering the priority level of each project, the effect of resilience factors on the capacity and each projects value distribution over time. Such paradox can be solved according to an artificial battle between contractors over the projects in the pipeline to mimic actual events. These complexities can by creating forces in the system for project priority, shocks and stresses, and value distributions in more advanced modelling stages (see Appendix M for more details).

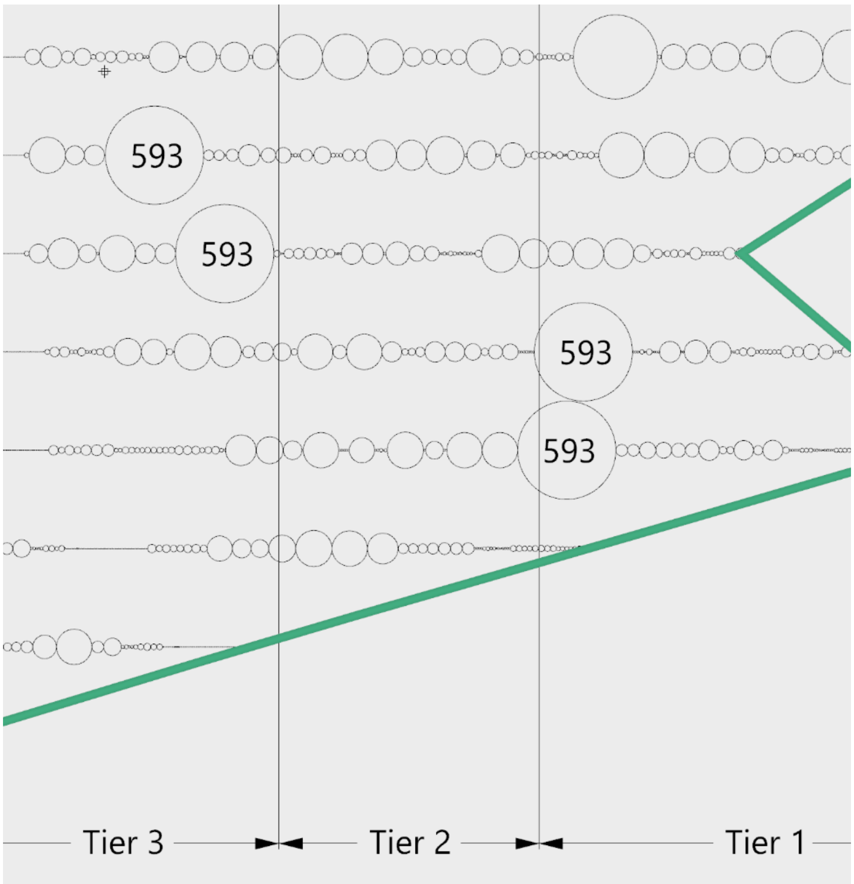

Figure 15 Tracking project value with Unicode

The same outputs were created for NZTA central region Data (Figure 16); with the same mapping technique used for MoE Data. The sector size for NZTA was unavailable at time. However, sector capacity was estimated based on historic data through the following two assumptions:

- Option 1-Lower limit of NZTA sector capacity for central region: is average work performed from 2019 to 2021 (3-year period due to less data availability for 2019)
- Option 2-Higher limit of NZTA sector capacity for central region; is average work performed in 2020 and 2021 period (2-year period due to more data availability in these years)

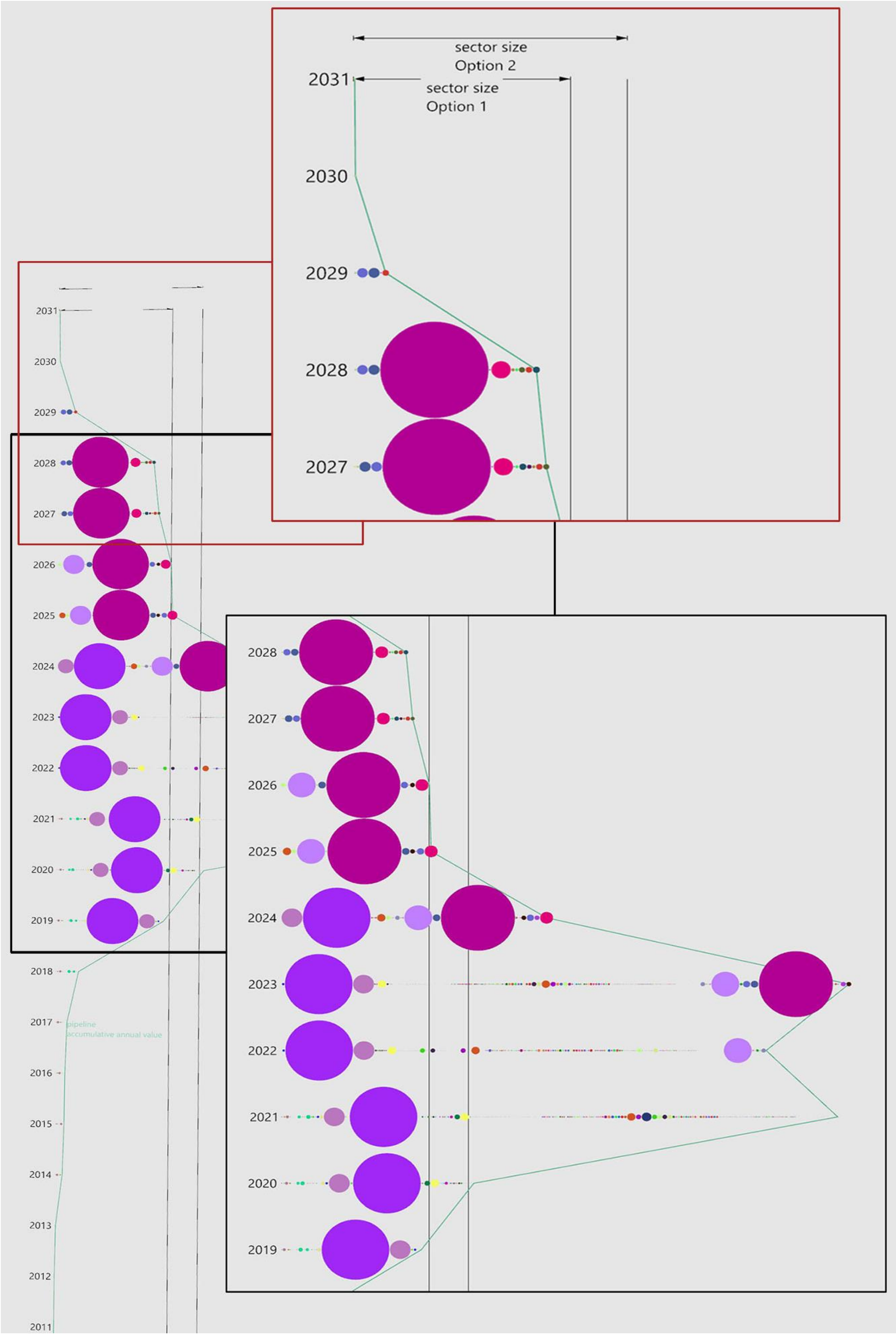

Figure 16 ABM for NZTA central region

Discussion

The initial comparator mechanism based on power query (step 4, Figure 1) and ABM (step 5, Figure 1); were only possible based on the common information framework developed and CanConstructNZ simplification assumptions. Although a meaningful comparison was possible based on these assumptions; the estimation accuracy has reduced due to the simplifications. However, the current accuracy level suffices programme objectives at this stage.

The comparator demonstrates a genuine lack of capacity for the sector to meet the demand of future work. The initial comparator mechanism approach via power query (Step 4) is extremely effective in providing practical outcomes to industry and potential stakeholders. It was demonstrated that demand forecasting is possible through time series analysis of quarterly pipeline value distributions. A dashboard was developed using Power BI data visualisation platform to customise the information for different uses (Figure 3).

The ABM technique is extremely effective in tracking of individual projects over time; in addition, to the evaluation of supply and demand. The ABM technique has the ability for more advanced assumptions and considering complexity in the model. These considerations can be associated to different tier contractor characteristics and project portfolios (Appendix L and M).

One of the limitations was the availability of standardised data at the time of reporting. In the initial comparator mechanism approach (step 4) outputs for the MoE Auckland region study was only possible. There was major gaps and missing values in the available data; specially within the pipeline information. Durations, start dates and values were missing for a significant portion of projects. However, with basic assumptions, the ABM approach was found to be suitable to both MoE and NZTA data. It was observed that variation of project size is much more extreme for NZTA projects in comparison to MoE projects. This could result in major fluctuations of demand for the sector associated to NZTA.

The aim was to understand, standardise data and develop a comparator mechanism; this report demonstrates a proof of concept for the mechanism. It also illustrates various forms of reliable and practical outputs these approaches produced. Both software used (Power BI and Grasshopper) are found to be suitable for further development of the model.

Conclusions and recommendations

As demonstrated the process of evaluating supply and demand for construction and infrastructure work is complex and time consuming. The FMW and case studies led to the development of a common information framework. The Relational Database Management System (RDBMS) approach was used to classify case study information based on the common information framework. However, the outputs exhibited for pipeline was not realistic and underrepresented. In addition, the sector size estimation was too complex to achieve.

Therefore, a series of simplification assumptions were suggested to make comparisons pf supply and demand possible. Both the power query based comparator and ABM demonstrated a lack of capacity for the sector to meet the demand of future work. Although there were limitations with data availability and there were accuracy issues with simplification assumption; this report has demonstrated a proof of concept for the comparator mechanism. The recommendations based on the report findings are as follows:

- The mechanism and models developed can be used for multiple database scenarios. Therefore, information and database standardisation are required to facilitate the comparator mechanism. This should be agreed and implemented across CanConstructNZ teams.

- Multiple databases can be assessed, and the data could be stacked across a range of major clients. In doing this the datasets must meet the requirements the comparator mechanism. Data screening is key, and all groups must screen data for missing values and gaps in the datasets.
- As mentioned the moderating effects of project priority, shocks and stresses should also be considered in relation to the current sector characteristics (tier and sub-contracting assumptions).
- Extending the model for three main regions identified in the CanConstructNZ assumptions to have a national cover. This can lead to identification of regional and typical forces; e.g. how sector size and projects load in NNI will have a dynamic effect on contractors' capacity in SI or SNI.
- Applying optimization techniques to find solutions for touching higher enhancing capacity and achieving higher capability levels (e.g., 3d movement for agents and rise their level of intelligence while space exploration).

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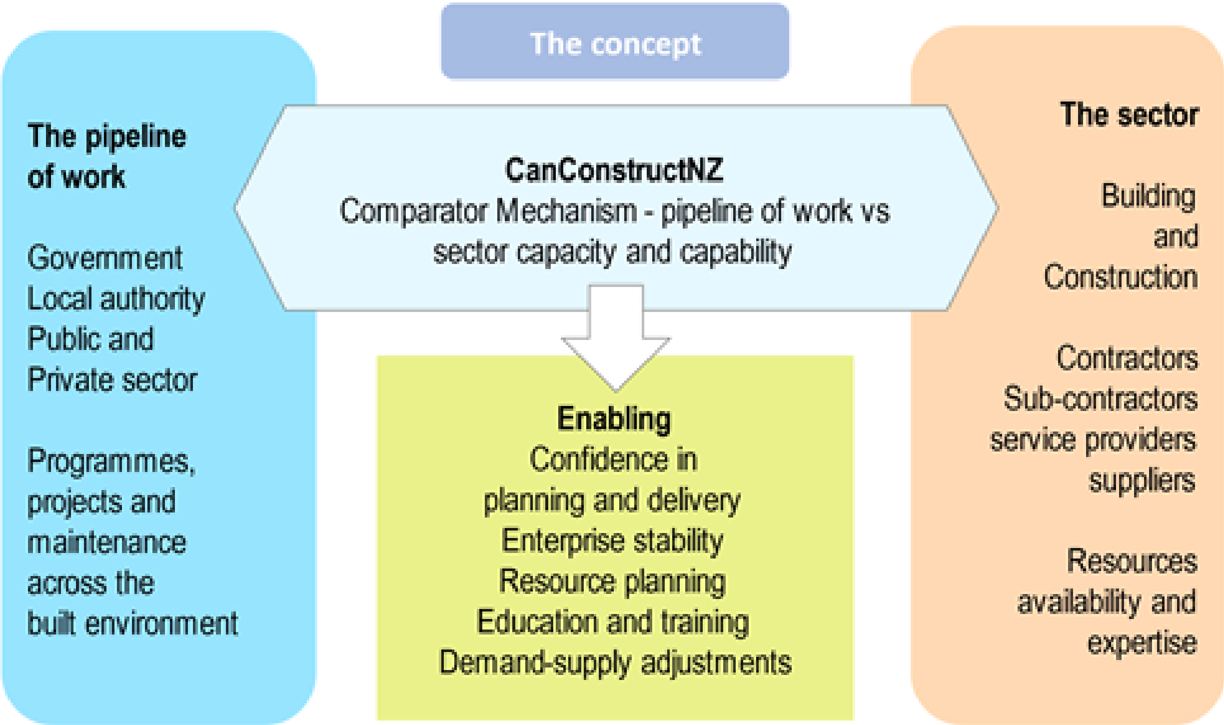
Appendix A: CanConstruct NZ research programme structure and teams



Team 1: Pipeline

Team 2: Vertical Sector

Team 3: Horizontal Sector

Team 4: Resilience

Team 5: Comparator Mechanism

Appendix B: Facilitated modelling workshops outcomes- Framing/capturing the problem

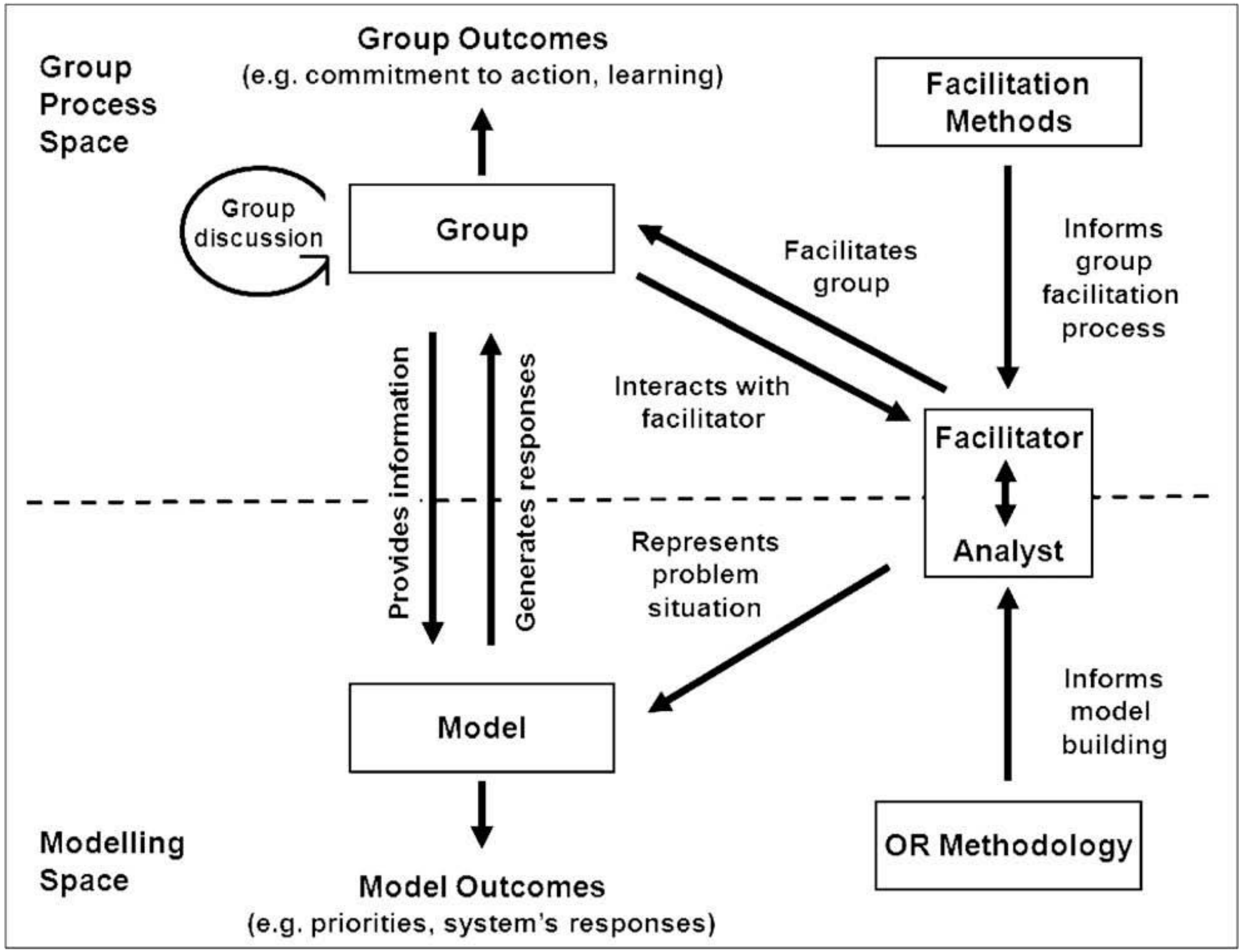


Figure 1 Facilitated modelling in operational research, Source: Franco and Montibeller (2010)

Table 1: Initial outcomes of facilitated modelling workshops:

Agreed Main Capacity Indicators for the construction sector (Discussions were based on available literature, existing findings and professional expertise).	• **Human Resource** • **Finance** • **Technologies /Equipment** • **Material**

Table Case study consideration and information classification

NZ Transport Agency			**Ministry of Education**			**Palmerston North Council**			**Dunedin Hospital**		
Project level			Project level			Sector			Mega project		
Sector level			Sector level			Regional Capacity					
Pipeline	**Sector**	**Resilience**	**Pipeline**	**Sector**	**Resilience**	**Pipeline**	**Sector**	**Resilience**	**P**	**S**	**R**
Value	Pre-qualification system	Covid	Ownership	Vertical	Covid	Value	(Divided into Horizontal and Vertical)		Programme: can be regarded as collection of smaller projects		
Location		Environmental	Value		Environmental	Classification					
Procurement method	Consultants	Social	Location	Pre-qualification requirement – (D, QS)	Political	Duration					
		Political	Procurement		Social	Procurement	Who are the Stakeholders?				
Duration/Time	Pre-qualification contractors	Economical	Duration/Time			Status					
Statuse			Status								
	stakeholders		Type of facility	Contractor							

NOMINAL Status Stakeholders

Ownership

Classification

Funding method

Figure: Picture taken of one from the outcomes of one of the facilitated modelling workshops.


NZTA
Project level
Sector Level
MOE
Project level
Sector level
PN
Sector
Regional Capacity
P
S
R
Value
location
Procurement method
Duration/time.
Type of project
Status
Prequalification System
Consultants
Pre-qualified contractors.
Stakeholders
Covid
environmental
Social
Political
Economical
ownership
Value
location
Procurement
Duration
time.
Type of facility
Status.
Vertical
D, QS
Pre qualification requirements
Contractors
Stakeholders.
Covid
Env.
Political
Social
Value
Classification
Duration
Procurement
Status
Capacity Indicator
-> Human Resource
-> Finance
-> Technology - equipment
-> Materia
Capacity at different level
Ownership
Classification
Funding method
NZTA
James
MOE
Nilwka
PN
Eric
DUN.
Regan
P
S
R
M
A
C
N

Appendix C: Facilitated modelling workshops outcomes- Initial request for information to case study team leaders

Mostafa Jelodar
Wed 3/2/2022 6:10 PM
To: Azam Zavvari;Niluka Domingo;James Rotimi;Regan Potangaroa;Amarachukwu Nwadike;An Le Thi Hoai;Arun Manickavasagam;Eric Scheepbouwer
Cc: Monty Sutrisna;Suzanne Wilkinson;Robert Mulligan <robert.mulligan@vuw.ac.nz>;Rod Cameron

CanConstruct team leaders ...
18 MB

Hi team,
Thanks for a good collaborative brainstorming session yesterday.
Currently we in the comparator team are looking at the following key point and we would appreciate your thoughts on them too:

Inclusion-exclusion criteria:
This could be separately done for pipeline and sector; or, it could be pipeline driven (i.e the project type could dictate the sector involvement and mapping). In any case we will need some criteria.
Regan's point on commitment and how it could be gaged can be considered as inclusion criteria for different projects.
Another observation is that these case studies could have unique criteria and specific timelines for inclusion in the pipeline (i.e Dunedin Hospital case has different phases at different time frames, do we consider all in our current model pipeline?)

Pipeline structure:
We need to know what the structure of the pipeline looks like for each project. Indicators and filter are needed, for instance:

- Value
- Location
- Procurement method
- Duration/Time
- Status
- stakeholders,
- etc.

Please refer to table circulated last week by Azam (attached CanConstruct teams workshop meeting 22nd of Feb). We could add to the indicators and filters list as we progress.

Sector mapping:
The sector mapping exercise will vary according to each case study. Hence a mapping strategy needs to be developed for each case study.
This can be achieved by looking at the supply chain and value chains in mapping the sector. An lee is currently using porters value chain to map all stakeholders; this can be a good practice exercise for each case.

Other notes:

- We could be looking at these cases as dynamic system and apply systems dynamic methodology. It requires decomposition of concepts and indicators.
- We need to know what primary indicators, and secondary indicator (which could have moderating affects) affecting capacity and capability (we could hold an industry focus group).
- We need to agree on the definition of capacity and capability.
- Power BI is being used as an initial platform for the comparator.

Please feel free to provide feedback and share your thoughts.
Best regards,
Mostafa

Appendix D: Facilitated modelling workshops outcomes- Detailed Request for information based on metrics

Team	Data and Information requirement	Data collected by (Person)	Feedback (other teams)
Pipeline	• The pipeline classifications and characteristics of projects • The pipeline exclusion and inclusion criteria • Project prioritisation systems • Historical information and databases available on different project types (Data/information of past projects for each case study; I.e. Value, location, procurement type, etc.) • High level Pipeline Model indicators to consider • Secondary/indirect influences/factors on pipeline	Azam, Arun, Amara In coordination with case study leads	
Resilience	• Shocks and stresses plus their likelihood • Separate effects of shocks and stresses on pipeline and sector • Short-term and long-term effect of these shocks and stress • Direct Vs Indirect effects of shocks and stresses • Resilience moderating factors for the model	Azam, Arun, Rob In coordination with case study leads	
Horizontal	• Sector mapping according to project characteristics • Prequalification and requirements for different project types • Historical information on the sector involvement in different types of projects • Secondary/indirect influences/factors on horizontal sector • High level sector Model indicators to consider	Azam, Arun, In coordination with case study leads	
Vertical	• Sector mapping according to project characteristics • Prequalification and requirements for different project types • Historical information on the sector involvement in different types of projects • Secondary/indirect influences/factors on vertical sector • High level sector model indicators to consider	Azam, Arun, An Lee In coordination with case study leads	
Comparator	• The data structure scrutiny • Agree and include model indicators for sector and pipeline • Considering capacity and capability definitions • Case study comparison of indicators and circumstances • The model concepts • The model reporting • Considering moderating factors	Mostafa, Azam, Arun, Roja, Parisa, Alice, Eric, Monty	

Mostafa Jelodar
Tue 3/15/2022 4:58 PM
To: Azam Zavvari;Niluka Domingo;James Rotimi;Regan Potangaroa;Amarachukwu Nwadike;An Le Thi Hoai;Arun Manickavasagam;Eric Scheepbouwer
Cc: Rod Cameron;Monty Sutrisna;Robert Mulligan <robert.mulligan@vuw.ac.nz>;Suzanne Wilkinson

Hi Team,
Thanks for another constructive session today. I have made some notes and as discussed I have created a table as to what information could be collected and useful for us as part of the case studies.
I have created a word file on MS teams with the information requirements from each team. Please click on the following link : Comparator Team Case stud requirements.
I realize that collecting all of this information may not be realistic with our current April deadline; but at least we can have a target and a discussion point as to what is needed. I have added a feedback column for you to provide feedback; and any feedback is welcomed. Please also do not hesitate to add points that I may have missed.
Hopefully in the next step we can look at timelines and key high level model indicators.
Best regards,
Mostafa

Dr Mostafa Babaeian Jelodar
PhD(Civil.En; Const.Mng), MSc (Proj.Mgt), BEng (Civil)
Senior Lecturer in Construction Engineering and Management
Co-Leader of Productivity in Built Environment Research Group

Academic Lead
School of Built Environment
College of Science
Massey University

Appendix E: Facilitated modelling workshops outcomes- Example of MoE Case study; data collection strategy and plan of actions

Pipeline:

Total pipeline value (based on timeline unit); this can be reported based on originals, actuals and other value breakdowns.

Project type: we can breakdown the value based on the following

- Combined
- Learning Support Modification
- LSPM
- New School
- New School Expansion
- Redevelopment
- Roll Growth

Pipeline: We need an assumption for the blank values (i.e. we can use averages for each band)?

Work type: New built, redevelopment, remediation

Educational Regions: value based on 10 locations

Number of projects in each value band for the country and each region.

The current list are the projects which have been approved.

Pipeline question: is there a priority system for these projects ?

Delivery Method

- Traditional
- Design & Build
- TBC
- Early Contractor Involvement
- PPP
- Modular
- Temporary Accommodation
- Other

Project Phase

- 11 Construction
- 09 Detailed Design
- 07 Prelim Design
- 06 Master Planning
- 10 Tender
- 08 Developed Design
- 15 On Hold
- 05 Initiation

- 14 Complete
- 13 Close Out
- 16 Cancelled
- 00 Pipeline
- 03 Business Case - CW
- 12 Defects
- 03 Business Case - S&P
- 02 PRF
- 00 Yet to enter
- 04 Pre-engagement

Pipeline question: We need an assumption to distributed value for different phases of various project types; could be based on project lifecycle analysis.

Sector:

MoE stakeholders (included in the database):

- Contractor
- QuantitySurveyor
- ProjectManager
- MasterPlanner
- LeadDesigner

We need to categorise the stakeholders involved; stakeholder screening is required to remove inconsistencies and avoid duplications?

Sector mapping question (according to project characteristics):

Based on pre-qualification how are stakeholders (Contractors, Project managers, master planner, lead designers, Quantity surveyors) assigned to what type of projects?

Are aloo the published stakeholder lists (the ones extracted by the sector team and included in MS teams) are the latest approved stakeholders for MoE and can they be included in any type of MoE projects?

What are the prequalification criteria? What is the inclusion and exclusion criteria for stakeholders involved in each project type?

Can we categorise stakeholders (specially contractors) based on MoE project types?

Is there a possibility for project life cycle assessment; choosing some of the representative projects and digging deeper into project phases.

Historical data inquiries

What is the portion of contractor involvement and contribution in MoE projects? Can this be extracted from Stats NZ or determined from some focused analysis.

What is the proportion of different type of contractor's contribution to the sector?

Are their indicators and stats of MoEs contribution and involvement to the construction sector? Historically how much of the sector are MoE projects? A breakdown if available?

Are there any project completion data available a simple list with the following information will be enough for now (we need as much as we get to for our model training datasets):

- Project value(originally approved value and final project value)
- Project type
- Start and end date (this is planned and actual)
- Location
- Main contractor
- Project consultants
- Sub-contractors
- Procurement type
- Other recorded information

Moderating effects on the project pipeline and sector:

What has caused changes to the pipeline of projects in different periods of time?

Can the direct effects and indirect affects be separated?

How has the sector coped with these changes and how did these changes influence the sector?

Some considerations for a more focused investigation based on sample of MoE Projects:

- Initial project approval
- Project status and the completion report
- Resource planning documents
- Master plan and schedule
- List of key stakeholders for the selected projects (based on client approval)
- Life cycle analysis for different project types.

Appendix F: Facilitated modelling workshops outcomes- Request for historical data

Mon 28/03/2022 1:17 PM

Mostafa Jelodar

RE: Project completion information

To Rod Cameron

Cc Monty Sutrisna; Suzanne Wilkinson

Hi Rod

Thanks for your email and the background information. I have had a conversation with Monty and we have thought of some quick and simplified ways of capturing completion/historical project information; which involves the following:

Database of previously completed projects (for each case study):

- Project value(originally approved value and final project value)
- Project type
- Start and end date (this is planned and actual)
- Location
- Main contractor
- Project consultants
- Sub-contractors
- Procurement type

A sample of projects for more focused analysis:

- Initial project approval
- Project status and the completion report
- Resource planning documents
- Master plan and schedule
- List of key stakeholders for the selected projects (based)

This is the information required at stage; more information may be required post our preliminary analysis.

Best regards,

Mostafa

Dr Mostafa Babaeian Jelodar

PhD(Civil.En; Const.Mng), MSc (Proj.Mgt), BEng (Civil)

Senior Lecturer in Construction Engineering and Management

Co-Leader of Productivity in Built Environment Research Group

Appendix G: Details of the comparative cross-case analysis

Pipeline characteristics: cross examination of the four cases (comparison of unique features of each case)

Project type - based on the nature of project the different case studies they have their own project type.			
MoE	NZTA	PNCC-Infracom	DH
Combined Learning Support Modification LSPM New School New School Expansion Redevelopment Roll Growth	**External funding Investment management Local road improvements Local road maintenance Public transport infrastructure Public transport services Road to Zero State highway improvements State highway maintenance Walking and cycling improvements**	**Community Facilities Housing Transport Water Waste Management**	**Medical Facilities Infrastructure**
Location - The cases are allocated region or regions.			
MoE	NZTA	PNCC-Infracom	DH
Not Specified Waikato Wellington Taranaki/Whanganui/Manawatu Bay of Plenty/Rotorua/Taup Auckland Tai Tokerau Canterbury Otago/Southland Nelson/Marlborough/West Coast	**Gisborne Hawkes Bay Manawatu/Whanganui Taranaki**	**Auckland Canterbury Wellington Northland Manawatu - Whanganui Otago Bay of Plenty Hawke's Bay Gisborne West Coast Waikato Tasman Taranaki Nationwide Other Marlborough Southland Not Specified North Island Nelson South Island**	**Otago**
Value – value come in actual price forecast value or value band			
MoE	NZTA	PNCC-Infracom	DH
Actual cost of projects & under $500,000 $500,000 to $1,000,000 $1,000,000 to $5,000,000 $5,000,000 to $10,000,000 $10,000,000 to $20,000,000 $20,000,000 plus	**Actual cost of projects**	**< 1 million 1-5 million 5-25 million 25-50 million 50 – 100 million 100- 250 million 250-500 million 500 – 1 billion 1 billion + Not Disclosed**	**Actual Cost 1.47 billion**
Priority based on type			
MoE	NZTA	PNCC-Infracom	DH
-(High / Medium / Low) -(Medium / Low)	1 to 12	---	Fast-track provisions enacted by the Government

			Covid-19 recovery programme
Procurement method used			
MoE	NZTA	PNCC-Infracom	DH
00 Yet to enter 00 Pipeline 02 PRF 03 Business Case - CW 03 Business Case - S&P 04 Pre-engagement 05 Initiation 06 Master Planning 07 Prelim Design 08 Developed Design 09 Detailed Design 10 Tender 11 Construction 12 Defects 13 Close Out 14 Complete 15 On Hold 16 Cancelled	Construction Detailed Business Case Implementation Improvement to existing AMP Local road improvements Local road improvements (SPR) Local Roads - Work category n Pre-implementation* Programme business case Property Public transport infrastructure Public transport services Repayment Road to Zero Road to Zero (SPR) Single-Stage Business Case SPR - Work category n State highway improvements State Highways - Work category n Walking and cycling improvements Work category n	-To be determined -Design and construct -Alliance -Construct only -Early Contractor Involvement -Other -Public Private Partnership	Traditional Procurement

Sector characteristics: Cross examination of the four cases

Vertical vs Horizontal			
MoE	NZTA	PNCC	DH
Vertical	Horizontal	Vertical vs Horizontal	Vertical
Prequalification based on project type			
MoE	NZTA	PNCC	DH
Prequalification system in place	Prequalification system in place	Not specified	Not specified
Stakeholders			
MoE	NZTA	PNCC	DH
Schools and Kura Change Hubs Professional Advisory Group Subject Expert Groups Panel Leads and Working Groups Pathways Advisory Group	Regional Councils and Unitary Authorities Territorial Local Authorities NZTA Agents Transport Operators and Providers Contractors and Consultants NZ Police	CBD Forum with Council Police Tourism Orgs	Ministry of Health, Southern Health (Southern District Health Board), Dunedin City Council, Otago Regional Council, Iwi, Private Citizens, Education providers (including University of Otago and Otago Polytechnic)
The supply chain based on project type			
MoE	NZTA	PNCC	DH
Supplier panels – Education in New Zealand	• Meat processing companies in New Zealand range from small, single plant operations to some of New Zealand's largest companies. The four major companies supplying the majority of exported meat products are:	impacts-of-pniti-on-key-regional-projects-feb-2021.pdf (pncc.govt.nz)	• Structure: Nationally produced and regionally prefabricated (e.g. NZ Steel and Canterbury precast concrete). • Cladding: Regionally manufactured and assembled (e.g. window joinery and glazing, wall cladding and

	• AFFCO • Alliance Group • ANZCO Foods • Silver Fern Farms		roofing (to stimulate local industry and economy). • Building Services: Regionally manufactured and installed (mechanical and electrical systems). • FF&E: Regionally manufactured and installed (to stimulate local industry and economy). • Specialised biomedical equipment: Internationally manufactured. • Human resources: NZ-based consultants and contractors, manufacturers and fabricators, technical trades persons and apprentices, and labour, plus operational (medical, administrative and maintenance) staff. • General: Supply chains would be similar to Waipapa Christchurch Hospital (Acute Services) completed 2020 by the appointed ECE contractor for NDH, CPB Contractors.

Moderating affects

MoE	NZTA	PNCC	DH
• **Economic resilience** Supply Chain Skill Shortage Boomburst Decreased economic activity Increased economic activity • **Built Environment** Work onsite Design flaw Housing densification Contractual issues • **Natural environment** Climate change weather events Flooding Severe winds Erosions • **Social** Remote Working Covid-19 Demographic changes • **Governance of risk** Policy Elections			

Data structure and availability

Data Structure			
MoE	NZTA	PNCC-Infracom	DH
Structured and unstructured Annual reports/website /Interview	**Structured and unstructured Annual reports/website /Interview**	**Structured and unstructured** **Infracom : Pipeline-Data-14-02-22-Public-Version**	**Structured and unstructured**
Availability of data			
MoE	NZTA	PNCC-Infracom	DH
Data are not available **Singin required for access to data**	**Data are not available** **Singin required for access to data**	**Data are not available** **Singin required for access to data**	**Data are not available** **Singin required for access to data**

Table of case study characteristics and comparator considerations

Case Study	**Characteristics**	**Comparator Consideration**
Dunedin Hospital	Publicly funded Project, fixed location, large scale project, project can be a disruptor	The scope of work is relatively defined, not many in the sector capable of taking the project, project complexity adds to sector convolution and entanglement
Ministry of Education	Client organisation; government, national cover, mixed size projects in the pipeline, mainly vertical sector	Pipeline comprised of relatively defined building projects, a range of contractors and trades are involved from the sectors
Waka Kotahi NZ Transport Agency (NZTA)	Client organisation; government, national projects, mainly horizontal sector	Pipeline involves mixed-complexity projects, pre-qualified contractors in the sector (much more defined sector)
Palmerston North City Council	Local authority, regional Cover, mixed project types and sizes, mainly horizontal plus some vertical	Projects of different nature, more localised sector; dependency on other regions

Case one: Ministry of Education (MoE)

The Ministry of Education (MoE) formed in 1989, is Government's lead advisor on the education system which by itself is not an education provider. Ministry of education has work on numerous functions such as giving guidance to the government, provide learning resources, administering and providing information to the education sector (mostly vertical sector). Moreover, it provides support and delivers the findings, specialist services, management, and operation to the education providers. The Ministry of Education covers is nation-wide and covers New Zealand educational projects with more emphasis on school projects. The ministry of education mostly works in vertical sector and based on their funding they develop a new school or expansion or redevelopment of the current schools across the whole of New Zealand.

Case two: Waka Kotahi New Zealand Transport Agency (NZTA)

The Waka Kotahi New Zealand Transport Agency (NZTA) was established under the Crown Entities Act and is an organisation that forms part of New Zealand state sector. NZTA is based on the corporate model where the governance of the organisation is split from the management of the organisation. NZTA organisation nationally covers the whole New Zealand Projects, which is mostly focused on Horizontal sector projects all over New Zealand. In 2021 the NZTA produced a new strategy for providing an integrated land transport system to connect people, places, and products for a thriving New Zealand.

Case three: Palmerston North City Council (PNCC)

The Council's vision for Palmerston North is for every resident to be able to enjoy the benefits of living in a small city, with the advantages of a big city. The Council has set out five strategies that will achieve

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this vision linking it to the 10 Year Plan. The Council is committed to work alongside Rangitāne o Manawatū to achieve all our goals, in acknowledgement of their status and responsibilities as mana whenua. Figure 3 shows how the Council's strategies and plans are aligned to its vision and goals. Each strategy and its associated delivery plans relate to one of the Council's five goals for the city, i.e., a) an innovative and growing city, b) a creative and exciting city, c) a connected and safe community, d) an eco-city and e) a driven and enabling Council. This captures the desire for Palmerston North to be recognized for its great quality of life while at the same time offering the lifestyle, education, and business opportunities available in much larger cities.

Figure 17 Goals for Palmerston North and the strategies and plans that contribute towards it (source: pncc.govt.nz)

Case four: Dunedin Hospital (DH)

The new Dunedin hospital is set to be built in two stages – 1. an outpatient building which is planned to open in January 2025 and 2. an inpatient building planned to open in April 2028. The new hospital is also set to include 421 beds, 16 theatres (expandable to 21 theatres) and 30 ICU or high dependency beds with the outpatient building supporting greater delivery of ambulatory care.

The focus of the new hospital centres around the use of latest technology including patient flow around the hospital and better access to diagnostics and treatment spaces reducing unnecessary delays. This project is estimated to cost approximately 1.47 billion dollars during 2019-2028.

Appendix H: Data structure and availability-Categorical descriptive analysis

Ministry of Education (MOE) Case Study		
Data	Number based on categories	List of categories
Unique_Id	1438	
Region	5	Central North Central South Southern Not Specified Northern
School Id	776	
School (Name)	779	
Education Region	10	Not Specified Waikato Wellington Taranaki/Whanganui/Manawatu Bay of Plenty/Rotorua/Taup Auckland Tai Tokerau Canterbury Otago/Southland Nelson/Marlborough/West Coast
Electorate	66	
Project Type	7	Redevelopment New School New School Expansion Combined Roll Growth Learning Support Modifications LSPM
Project Phase	18	00 Yet to enter 00 Pipeline 02 PRF 03 Business Case - S&P 03 Business Case - CW 04 Pre-engagement 05 Initiation 06 Master Planning 07 Prelim Design 08 Developed Design 09 Detailed Design 10 Tender 11 Construction 12 Defects 13 Close Out 14 Complete 15 On Hold 16 Cancelled
Delivery Method	8	Traditional Design & Build TBC Early Contractor Involvement PPP Modular Temporary Accommodation

		Other
QuantitySurveyor	70	
ProjectManager	80	
MasterPlanner	83	
LeadDesigner	102	
Contractor	122	
Tender Release	320 2015-2024	
Construction Start Date	379 2013-2024	
Difference in Months between Tender Release and Construction Start	231	
Estimated Completion	2014-2028	
Practical Completion	2015-2025	
Construction Budget	898	
Assumed Total Budget	858	
K2 Authorised	168	
Proposed Value Band	6	

Waka Kotahi NZ Transport Agency (NZTA) Case Study		
Data	Number based on categories	List of categories
Total cells	801	
Activity id	242	Not Unique
Phase id	801	Unique
SAP Initiative Id	95	
SAP Item Id	165	
Region	1	Central
Local government region		Gisborne Hawkes Bay Manawatu/Whanganui Taranaki
Org id	25	
Org name	25	
Org Type	2	Approved Organisation NZTA-Region
Activity name	165	External funding Investment management Local road improvements Local road maintenance Public transport infrastructure Public transport services Road to Zero State highway improvements State highway maintenance Walking and cycling improvements
SAP Initiative Name	82	
Public Name	21	
Strategic context	159	text
Primary Benefit & Measure	40	
Project Background		
NZTA assessment of GPS alignment NZTA assessment of scheduling		

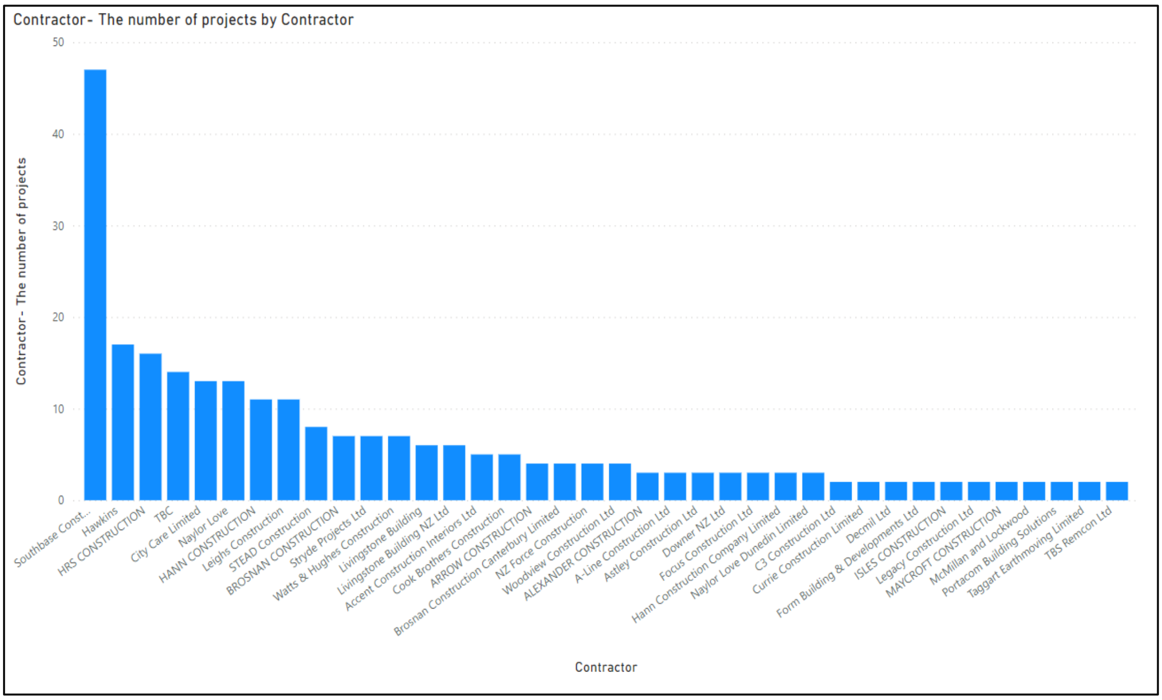
NZTA assessment of efficiency NZTA Profile		
NZTA Priority		1 to 12
Phase type		Construction Detailed Business Case Implementation Improvement to existing AMP Local road improvements Local road improvements (SPR) Local Roads - Work category n Pre-implementation* Programme business case Property Public transport infrastructure Public transport services Repayment Road to Zero Road to Zero (SPR) Single-Stage Business Case SPR - Work category n State highway improvements State Highways - Work category n Walking and cycling improvements Work category n
AC code AC name WC code WC name		
Funding source	6	NLTF External funding - Provincial Growth Fund External funding - Supergold card External funding - Regional Investment Opportunities External funding - Infrastructure Fund (Capital Investment Package)
Status	4	Funding Approved Under Review-Included in NLTP 2021-24 Included in NLTP 2021-24 Under Review-Funding Approved
Start year	2009-2027	
End year	2021-2031	
Duration (Years)		1 to 13
Total cost all years 2021/22 total cost 2022/23 total cost 2023/24 total cost Total cost 3 years		
Next year's total cost		
Funding Priority	4	Approved Probable Committed Possible

PNCC (PNCC organisation listed based on Infracom)		
Data	Number based on categories	List of categories
PrimaryKey	71	Unique id
DateUpdated	71	Text
ProcuringAgencyOrganisation	71	text
ProjectName	blank	
ProjectShortDescription	blank	
ParentProjectID	blank	
ProjectStatus		Early Planning Under Construction In Planning In Procurement
FundingStatus		
ProcurementType		
ProcurementMethod		
ProjectRegion		
ProjectCityTown	blank	
ProjectSuburb	blank	
ProjectSector	5	Community Facilities Transport Housing Water Waste Management
EstimatedProjectValueRange	3	5 - 25 Million 1 - 5 Million < 1 Million
EstimatedQuarterBusinessCaseStart	blank	
EstimatedQuarterBusinessCaseCompletion	blank	
EstimatedQuarterProcurementStart	blank	
EstimatedQuarterProcurementCompletion	blank	
EstimatedQuarterConstructionStart	blank	
EstimatedQuarterConstructionCompletion		
EstimatedQuarterProjectRangeStart	Just 4 projects listed	2026-Q3 2021-Q3 2020-Q3 2020-Q1
EstimatedQuarterProjectRangeCompletion	Just 3 projects listed	2028-Q2 2022-Q2 2021-Q4
ProjectInfoURL	Just 1 project url listed	URL
EstimatedProjectValueNote		
Contact		
Latitude Longitude		

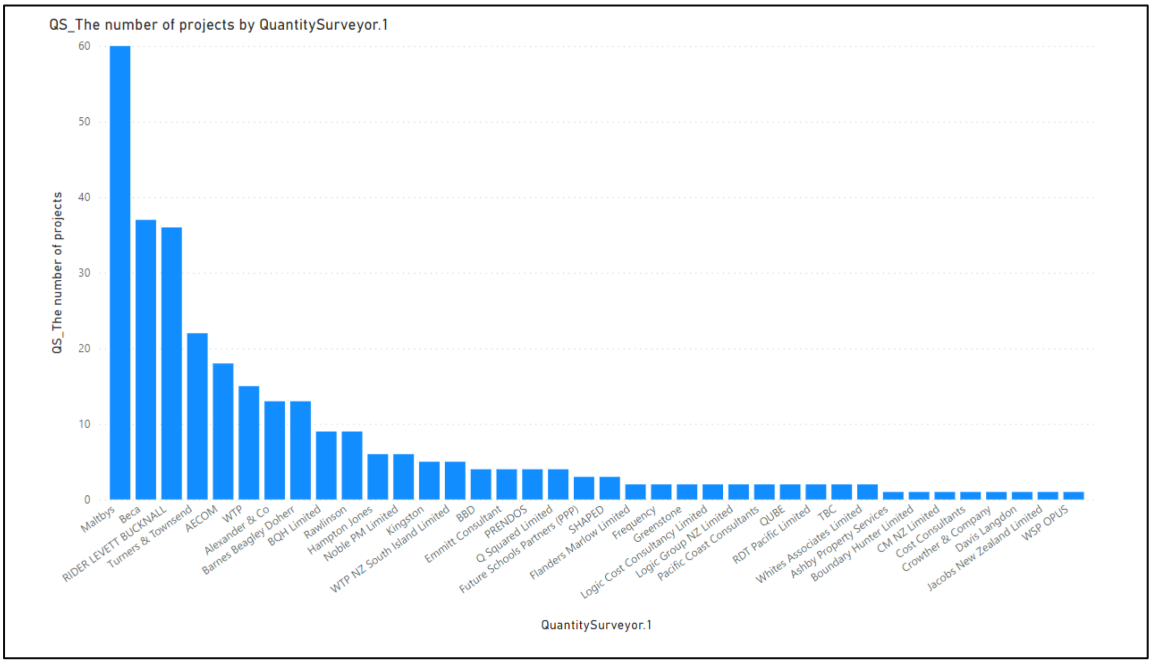
Dunedin Hospital	
Data	information
Project type,	Medical Facilities Infrastructure
Location	Otago
Value (need to agree on value bands for each case study)	Actual Cost 1.47 billion
Priority based on type	Fast-track provisions enacted by the Government Covid-19 recovery programme
Procurement method used	Traditional Procurement
Vertical vs Horizontal	Vertical
Prequalification based on project type	Yes
Stakeholders	Ministry of Health, Southern Health (Southern District Health Board), Dunedin City Council, Otago Regional Council, Iwi, Private Citizens, Education providers (including University of Otago and Otago Polytechnic)
The supply chain based on project type	Structure: Nationally produced and regionally prefabricated (e.g. NZ Steel and Canterbury precast concrete). Cladding: Regionally manufactured and assembled (e.g. window joinery and glazing, wall cladding and roofing (to stimulate local industry and economy). Building Services: Regionally manufactured and installed (mechanical and electrical systems). FF&E: Regionally manufactured and installed (to stimulate local industry and economy). Specialised biomedical equipment: Internationally manufactured. Human resources: NZ-based consultants and contractors, manufacturers and fabricators, technical trades persons and apprentices, and labour, plus operational (medical, administrative and maintenance) staff. General: Supply chains would be similar to Waipapa Christchurch Hospital (Acute Services) completed 2020 by the appointed ECE contractor for NDH, CPB Contractors.

Appendix I: Case Studies result and visualisation

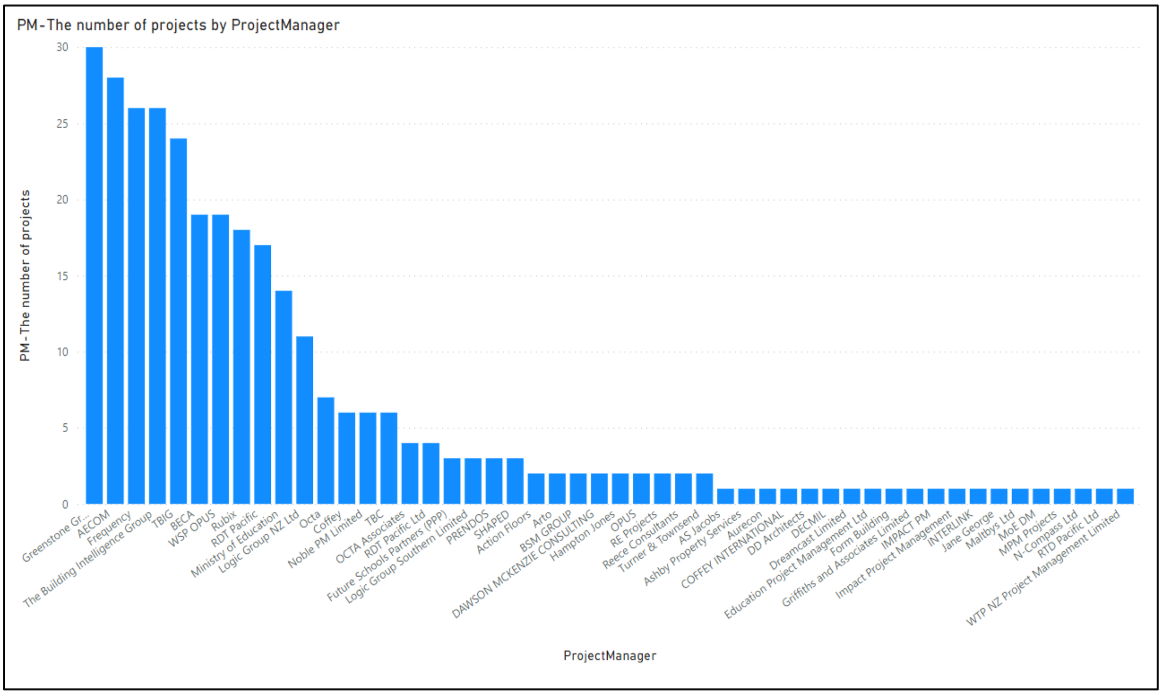
The number of projects by contractors based on MOE data



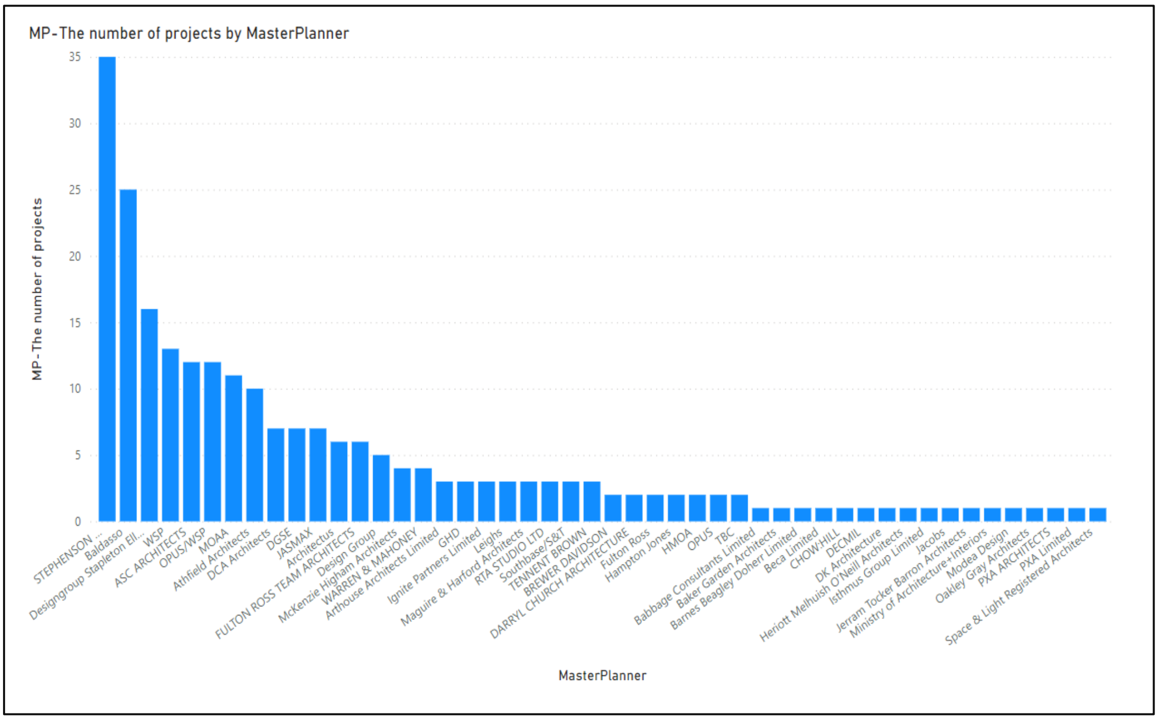
The number of projects by Quantity Surveyors based on MOE data



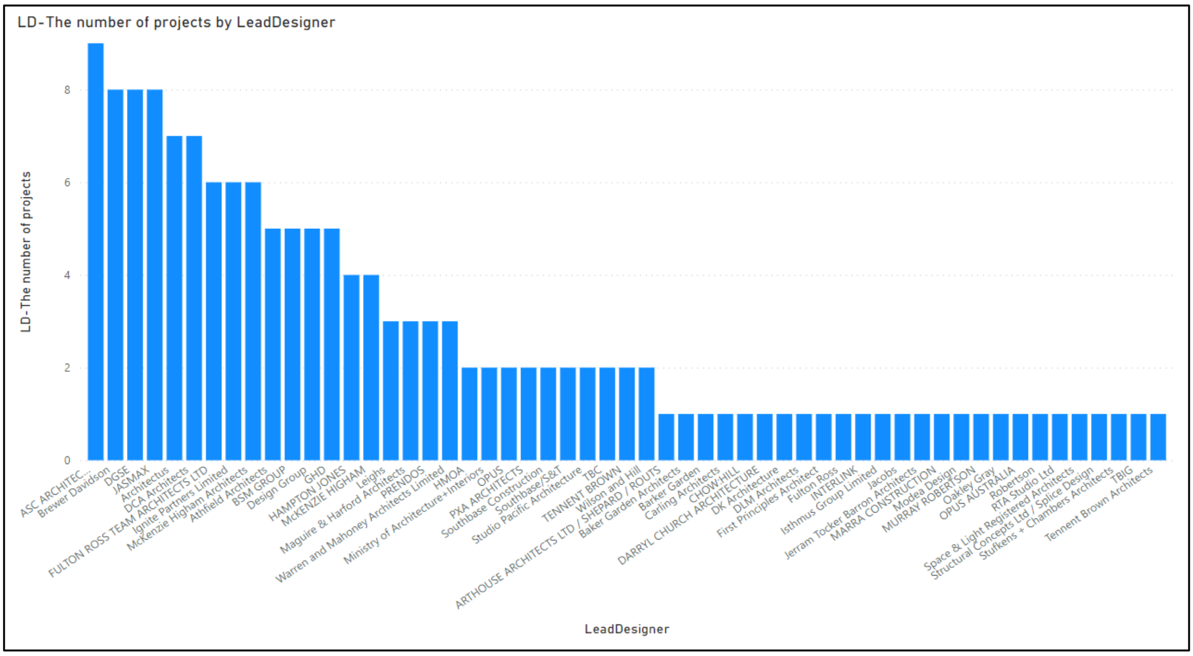
The number of projects by Project Managers based on MOE data



The number of projects by Master Planner based on MOE data



The number of projects by Lead Designer based on MOE data



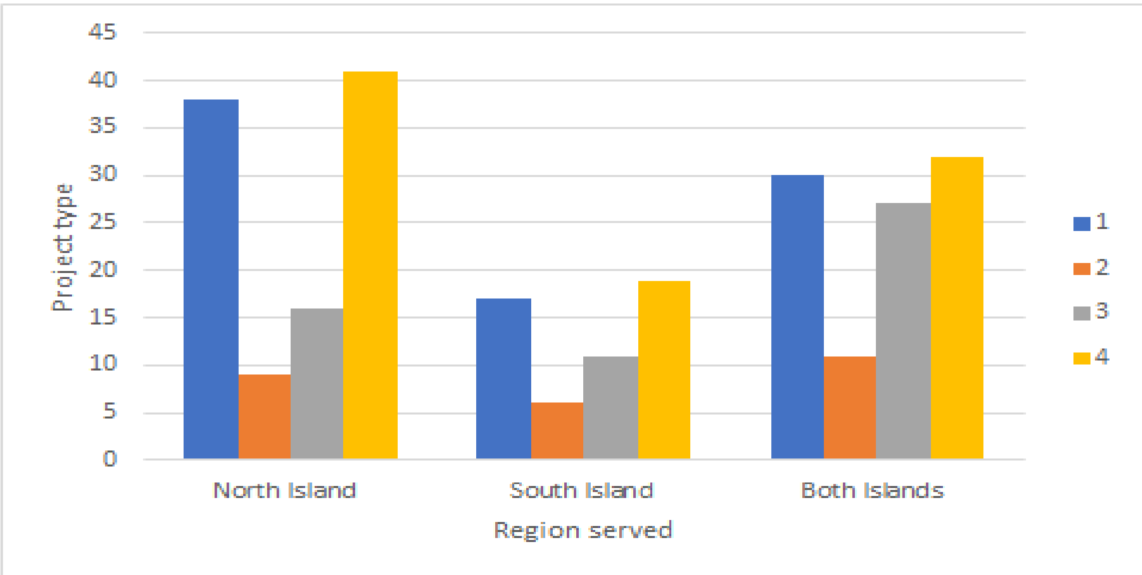


Figure 11 Distribution of contractors based on the three different regions served and the type of project.

Auckland				
Quantity Surveyor	Project Manager	Master Planner	Lead Designer	Contractor
Rawlinsons	N/A	N/A	N/A	Legacy Construction Ltd

Barney Beagley Doherr Limited	Rubix	ASC Architects Limited	Ministry Of Architrcture + Interriors	Woodview
Whites Associates Limited	Maltbys Ltd	Ignite Partners Limited	Ignite Partners Limited	Southbase Construction
BQH Limited	Greenstone Group Ltd	Warren And Mahoney Limited	Warren And Mahoney Limited	Astley Construction Ltd
Turner And Townsend	Dreamcast Limited	Barnes Beagley Doherr Limited	GHD Limited	Stryde Projects Limited
Greenstone Group Limited	AECOM	GHD	Brewer Davidson	NZ Force Construction
AECOM Limited	RDT Pacific	Stephenson And Turner NZ Ltd	GHD	RDT Pacific
Maltbys	Frequency	Beca Limited	WSP New Zealand Limited	NZ Force Construction
Whites Associates LTD	RDT Pacific Ltd	Babbage Consultants Limited	Warren And Mahoney Architects Limited	A-Line Construction Ltd
Jacobs New Zealand Limited	Rubix Limited	RTA Studio Ltd	RTA Studio Ltd	Downers NZ Ltd
Maltbys Ltd	AS Jacobs		Brewer Davidson Limited	C3 Construction Ltd
AECOM New Zealand Limited	Frequency NZ Limited		Ignote Partners Limited	Focus Construction Ltd
Kingston Partners Ltd	MPM Projects		BSM Group Architects	Accent Construction Interiors
N/A	Beca Ltd		BSM Group Architects Limited	Accent Construction Interiors Ltd
Turners & Townsend	RDT Ltd		MOAA Architects Ltd	Focus Construction
WTP New Zealand Limited WTP Partnership	Coffey		Form Building And Developments	Cassidy Construction Ltd
Emmitt Consultant	Education Project Management Ltd		DLM Architects	Watts & Hughes
Emmitt Consultant	Beca			Stryde Projects Ltd
Rider Levett Bucknall Auckland Ltd	Moe DM			Stead Construction Limited
WTP New Zealand Limited WT Partnership	Greenstone Group Limited			N/A
Kingstons	Hampton Jones			Miro Projct Management
	TBIC			Woodview Construction Ltd
	TBIG			TBS Remcon Ltd
	N-Compass Ltd			Mainline Construction
	RTD Pacific Ltd			Form Building & Developments Ltd
	WTP NZ Project Management Limited			Decmil Ltd
				Downer NZ Ltd
				Accent Construction Interiors Limited
				Savory Construction Ltd
Blanks				
629	600	652	637	613

Bay Of Plenty/Rotorua/Taupo

Quantity Surveyor	Project Manager	Master Planner	Lead Designer	Contractor
		DCA ARCHITECTS		

Crowther & Company	Frequency	DCA Architects	DCA Architects	Stead Construction
Blanks				
3	3	2	3	3
Canterbury				
Quantity Surveyor	Project Manager	Master Planner	Lead Designer	Contractor
RLB	TBC - Expected Sept 21	TBC - Expected April 21	N/A	TBC - Expected Sept 21
Future Schools Partners (PPP)	Future Schools Partners (PPP)	ASC Architects (PPP)	ASC Architects (PPP)	Hawkins Construction (PPP)
BBD	TBIG	Leighs	Leighs	Leighs
Maltbys	Aecom	BALDASSO CORTESE NOORDANUS	BALDASSO CORTESE NOORDANUS	TBC - Expected Jan 22
Aecom	WSP Opus	Hampton Jones	Hampton Jones	TBC - Expected Oct 21
WT Partnership	Beca	Stephenson & Turner	Stephenson & Turner	City Care
Rider Levett Bucknall Christchurch	The Building Intellingence Group	Jasmax	WSP	Hawkins Construction Ltd
Rawlinson	SHAPED	Baldasso	Baldasso	Hawkins
Turner & Townsend	Greenstone Group	Southbase/S&T	Southbase/S&T	Hann Construction
SHAPED	Opus	Design Group	Design Group	Southbase Construction
Alexander & Co	RDT PACIFIC	DGSE	DGSE	Cook Brothers
RIDER LEVETT BUCKNALL		ASC ARCHITECTS	ASC ARCHITECTS	Hann
		Baldasso Cortese	Baldasso Cortese	SOUTHBASE/CPP
		ARCHITECTUS	ARCHITECTUS	HRS Construction
Blanks				
19	20	19	19	19
Nelson/Marlborough/West Coast				
Quantity Surveyor	Project Manager	Master Planner	Lead Designer	Contractor
Noble PM Limited	Noble PM Limited	MOAA Architects Limited	MOAA Architects Limited	Brosnan Construction Canterbury Limited
Q Squared Limited	RDT Pacific Limited	WSP NZ Limited	WSP NZ Limited	CYB Construction
WTP NZ South Island Limited	RE Projects	Arthouse Architects Limited	MOAA ARCHITECTS LTD	FITZGERALD
Turner & Townsend	THE BUILDING INTELLIGENCE GROUP LIMITED	MOAA ARCHITECTS LTD	Fulton Ross	Fitzgerald Construction Limited
	Octa	Fulton Ross	ARTHOUSE ARCHITECTS LTD / SHEPARD / ROUTS	
	RE Projects	ARTHOUSE ARCHITECTS LTD / SHEPARD / ROUTS		
Blanks				
21	21	21	23	29
Otago/Southland				

Quantity Surveyor	Project Manager	Master Planner	Lead Designer	Contractor
BECA Limited	N/A	Stephenson & Turner NZ Ltd	Stephenson & Turner NZ Ltd	Southbase Construction
Rawlinson	Frequency	Designgroup Stapleton Elliott	Oakley Gray	Jones & Cooper
QUBE	Logic Group	TBC - Expected May 21	Designgroup Stapleton Elliott	Cook Brothers Southern Lakes
Beca	TBIG	Baldasso	TBC - Expected May 21	TBC - March 22
Logic Group NZ Limited	Beca	Athfield Architects Limited	Baldasso	ABL
Rider Levett Bucknall (BC Only-Engagement Complete)	Reece Consultants	Athfield Architects (BC Only-Engagement Complete)	Ignite Partners Limited	TBC -Expected Oct 21
BEA Limited	Logic Group Southern Limited	Ignite Partners Limited	DK Architecture	Portacom NZ Ltd
RDT Pacific Limited	The Building Intelligence Group	DK Architecture	N/A	Southbase Construction
Rawlinsons	Reece Building Consultants	N/A	Stephenson & Turner	Naylor Love - Dunedin
Logic Cost Consultancy Limited	Jane George	Stephenson & Turner	Maguire & Harford Architects	Breen Construction
Flanders Marlow	Future Schools Partners (PPP)	Maguire & Harford Architects	Baker Garden Architects	Naylor Love
Rider Levett Bucknall		Baker Garden Architects	Athfield Architects	Naylor Love Dunedin Limited
Barnes Beagley Doherr		Athfield Architects	Oakley Gray Architects	Amalgamated Builders Limited
Logic Group		Oakley Gray Architects	Baldasso Cortese K2	Brosnan Construction Canterbury Limited
WTP NZ South Island Limited		Baldasso Cortese K2	Baldasso Cortese Noordanus	Cook Brothers Construction
Flanders Marlow Limited		Baldasso Cortese Noordanus	Barker Garden	Hawkins Construction (PPP)
Future Schools Partners (PPP)		ASC Architects (PPP)	ASC Architects (PPP)	
Blanks				
93	94	97	98	96
Tai Tokerau				
Quantity Surveyor	Project Manager	Master Planner	Lead Designer	Contractor
Maltbys	Hampton Jones	Ministry Of Architecture+Interiors	Ministry Of Architecture+Interiors	Arco
Kingstons	WSP Opus	ASC Architects Ltd		Portacom Building Solutions
Pacific Coast Consultants	Arto			A Line Construction Limited
Boundary Hunter Limited	Griffiths And Associates Limited			
Blanks				
93	94	97	98	96
Taranaki/Whanganui/Manawatu				

Quantity Surveyor	Project Manager	Master Planner	Lead Designer	Contractor
Maltbys	Aecom	Designgroup Stapleton Elliott	Designgroup Stapleton Elliott	Livingstone Building
Rider Levett Bucknall	Wsp Opus	Stephenson & Turner	Stephenson & Turner Limited / Designgroup Stapleton Elliott	Southcoast Construction
Prendos	Bsm Group		Murray Robertson	Livingstone Building Nz Ltd
Davis Langdon	Impact Pm		Dgse	Livingstone Building
	Ministry		Stephenson & Turner	Pepper Construction
	Prendos		Bsm Group	Maycroft Construction
	Impact Project Management		Prendos	Isles Construction
				Alexander Construction
				Livingstone Building Ltd
Blanks				
15	15	30	15	16
Waikato				
Quantity Surveyor	Project Manager	Master Planner	Lead Designer	Contractor
Maltbys	Action Floors	Asc Architects	Jasmax	Livingstone Nz Ltd
Beca	Frequency Projects	Chow:Hill	Moaa Architects	Arrow
Shaped	Frequency	Asc Architects (Ppp)	Chow:Hill	Arrow Construction
	RDT PACIFIC		ASC ARCHITECTS (PPP)	Livingstone Building NZ Ltd
	MINISTRY			STEAD CONSTRUCTION
	SHAPED			Livingstone Buildings NZ Ltd
				CPB / SOUTHBASE JV (PPP)
blanks				
29	27	30	29	27
Wellington				
Quantity Surveyor	Project Manager	Master Planner	Lead Designer	Contractor
Maltbys	Coffey	Mckenzie Higham Architects	Mckenzie Higham Architects	HAWKINS 2017 LTD
Hampton Jones	Frequency	Designgroup Stapleton Elliott	DGSE	Naylor Love
AECOM	The Building Intelligence Group	Jerram Tocker Barron Architects	WSP	Southbase Construction Ltd
BECA	AECOM	Isthmus Group Limited	Designgroup Stapleton Elliott	Hawkins Construction
RIDER LEVETT BUCKNALL	COFFEY INTERNATIONAL	WSP Opus	Jerram Tocker Barron Architects	HOLMES CONSTRUCTION GROUP LTD

Ashby Property Services	TBIG	OPUS	Mckenzie Higham Limited	Peryer Construction Limited
Cost Consultants	Ashby Property Services	WSP	Mckenzie HIGHAM	Naylor Love Construction Ltd
WT Partnership	BSM GROUP		Stephenson & Turner	ISLES CONSTRUCTION
WTP	OCTA Associates		HAMPTON JONES	Arrow Construction
			Robertson	Maycroft Construction
			STEPHENSON & TURNER LIMITED	
			Isthmus Group Limited	
			Studio Pacific Architecture	
			OPUS	
blanks				
68	81	87	64	83

NZTA sector side

Legends

NI	North Island
BI	Both Islands
SI	South Island
1A	Routine and Minor works > $20 million
1B	Routine and Minor works $5 - $20 million
1C	Routine and Minor works $0.5 - $5 million
1D	Routine and Minor works < $0.5 million
2A	Surfacing > $20 million
2B	Surfacing $5 - $20 million
2C	Surfacing $0.5 - $5 million
2D	Surfacing < $0.5 million
3A	Bridge construction > $20 million
3B	Bridge construction $5 - $20 million
3C	Bridge construction $0.5 - $5 million
3D	Bridge construction < $0.5 million
4A	General Horizontal Construction > $20 million
4B	General Horizontal Construction $5 - $20 million
4C	General Horizontal Construction $0.5 - $5 million
4D	General Horizontal Construction < $0.5 million

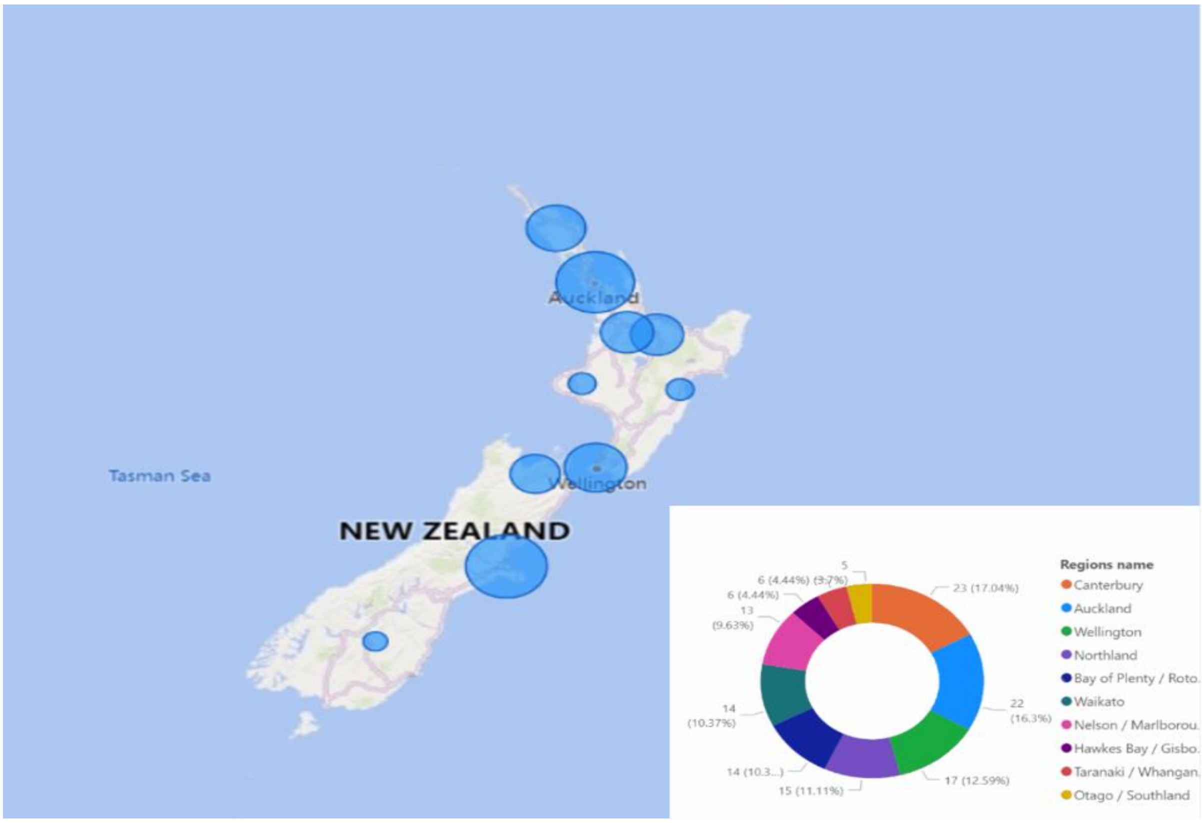
Name of the contractor	Region of operation	City based at	Value Band
Dempsey Wood Civil Limited	NI	Auckland	1A, 2A, 3A, 4A
InframaxConstruction Ltd	NI	Te Kuiti	1A, 2B, 4A
J Swap Contractors Limited	NI	Matamata	1A, 4A
Quality Roading and Services Ltd	NI, BI	Wairoa	1A, 3A, 4A
Splice Construction Ltd	NI	Hamilton	1A, 4A
Stringfellow Contracts Ltd	NI	Palmerston North	1A, 4A
Total Infrastructure Ltd	NI	Auckland	1A, 3C
United Civil Construction Ltd	NI	Whangarei	1A, 3A, 4A
Wharehine Construction Ltd	NI	Wellsford	1A, 4A
Base Civil Limited	NI	Hamilton	1B, 4B
CSL Infrastructure	NI	Auckland	1B, 4B
Inline Group Ltd	NI	Gisborne	1B, 3D
McKenzie & Parma Limited	NI	Auckland	1B, 4B
McNatty Construction	NI	Napier	1B, 3B, 4B
Mills Albert Ltd	NI	Paraparaumu	1B, 4B
Russell Roads Limited	NI	Hastings	1B
Troy Wheeler Contracting Ltd	NI, BI, SI	Papakura	1B, 4B, 3C
Waiotahi Contractors Ltd	NI	Whakatane	1B, 4B
Asset Construction Limited	NI	Auckland	1C, 4C
Auckland Glasspro Ltd	NI	Auckland	1C
Combined Road &Traffic Services Ltd	NI	Rotorua	1C
McKay Cartage Limited	NI	Gisborne	1C, 4C
Northland Transport Ltd	NI	Kerikeri	1C, 4C
Orsborn Roadmakers Ltd	NI	Frimley	1C
Sight Traffic Management Systems Ltd	NI	Tauranga	1C
Spray Marks NZ	NI	Tauranga	1C
Steve Bowling Contracting Limited	NI	Whangarei	1C, 4C
Taranaki Civil Construction Limited	NI	Inglewood	1C
Tascon 2019 Ltd	NI	Poruria	1C, 4C
TCD Civil Construction Ltd	NI	Auckland	1C, 4C
Topline Contracting Limited	NI	Hastings	1C, 4D
Whitaker Civil Engineering Ltd	NI	New Plymouth	1C, 4C
Aco Waikato Ltd	NI	Morrinsville	1D
Earthworx Rural and Civil Limited	NI	Whangarei	1D, 4D

Kuru Contracting Limited	NI	Tolaga Bay	1D, 4D
Scanpower Ltd	NI	Dannevirke	1D
SuperSealing Ltd	NI	Papamoa	1D
Tairawhiti Contractors Ltd	NI	Rotorua	1D
Total Infrastructure Ltd	NI	Auckland	2A, 4A
J & J Walters Ltd	NI	Marton	2B
McKenzie & Parma Limited	NI	Auckland	2B
Quality Roading and Services Limited	NI	Wairoa	2B, 3A
Russell Roads Limited	NI	Hastings	2B, 4B
Aco Waikato Ltd	NI	Morrinsville	2D, 4D
J Swap Contractors Limited	NI	Matamata	2D, 3B
Silverstrand Pty Ltd	NI	Poruria	3B, 4B
Spartan Construction Ltd	NI	Hamilton	3B, 4B
Bridge It NZ Limited	NI	Tauranga	3C
Currie Construction Ltd	NI	Gisborne	3C, 4C
Exaro Contracting Ltd	NI	Auckland	3C
Lattey Group	NI	Hastings	3C
Siteworx Civil Ltd	NI	Gisborne	3C, 4C
Steve Bowling Contracting Limited	NI	Whangarei	3C
Taranaki Civil Construction Limited	NI	Inglewood	3C, 4B
Whitaker Civil Engineering Ltd	NI	New Plymouth	3C
Goodman Contractors Limited	NI	Kapiti Coast	4A
ID Loader Limited	NI	Whanganui	4A
Cambridge Construction Company Limited	NI	Hamilton	4B
EPL Construction Limited	NI	Whangamata	4C
ICB Retaining & Construction Limited	NI	Auckland	4C
MAP Projects Ltd	NI	Mount Maunganui	4C
Maxbuild Ltd	NI, BI	Auckland	4C, 3B
Online Contractors 2016 Ltd	NI	Hamilton	4C
Ontrack Contracting Ltd	NI	Paeroa	4C
Nick Pemberton Construction Limited	NI	Rukuhia	4D
Abergeldie Complex Infrastructure Limited	BI	Auckland	1A, 2C, 3A, 4A
Armitage Systems Limited	BI	Albany	1A
City Care Limited	BI	Christchurch	1A, 2A, 4A
CLL Service and Solutions Limited	BI	Kumeu	1A, 3A, 4A
Downer New Zealand	BI	Auckland	1A, 2A, 3A, 4A
Fulton Hogan Ltd	BI	Christchurch	1A, 2A, 3A, 4A
HEB Construction Limited	BI	Auckland	1A, 2A, 3A, 4A
Hick Bros Civil Construction Ltd	BI	Auckland	1A, 4A
Higgins Contractors Ltd	BI	Hastings	1A, 2A, 3A, 4A
John Fillmore Contracting Ltd	BI	Auckland	1A, 2B, 4A
McConnell Dowell Constructors Ltd	BI	Auckland	1A, 2A, 3A, 4A
Taylors Contracting Company Limited	BI	Nelson	1A, 4A
Ventia NZ Operations Limited	BI	Auckland	1A, 2A, 4A
Wagners Holding Company Ltd	BI	Toowoomba	1A, 3A
WSP New Zealand Ltd	BI	Auckland	1A
CB Civil & Drainage Ltd	BI	Auckland	1B, 2B, 3B, 4A
Conspec Construction Ltd	BI	Tauranga	1B, 3B, 4B
GeoStabilization New Zealand Ltd	BI	Auckland	1B, 4B
Maxbuild Ltd	BI	Auckland	1B
Riverside Construction Limited	BI	Levin	1B, 3B, 4B
Schick Civil Construction	BI	Hamilton	1B, 4B
CMT Group NZ Limited	BI	Blenheim	1C, 4C
Concrete Structures (NZ) Ltd	BI	Rotorua	1C, 3B, 4B
Directionz Limited	BI	Auckland	1C
Grant Hood Contracting Ltd	BI	Ashburton	1C, 4C
Heads Up Access Ltd	BI	Redcliffs	1C, 3C, 4C
HTS Group Ltd	BI	Wellington	1C
Ross Roadmakers Limited	BI	Auckland	1C
Spray Marks Road Marking Limited	BI	Ashburton	1C
Traffic Systems Limited	BI	Auckland	1C, 2D, 4C
Johnstone & Masters Ltd	BI	Rotorua	2C
Acciona Construction Australia Pty Ltd	BI	Australia	3A, 4A
CPB Contractors Pty Limited	BI	Auckland	3A, 4A
John Holland	BI	Auckland	3A, 4A
TBS Farnsworth	BI	Auckland	3A
Geovert Limited	BI	Auckland	3A, 4B
Concrete Solutions Limited	BI	Wellington	3C
Concrete Treatments NZ Limited	BI	Tuakau	3C, 4C
Construction Techniques Ltd	BI	Auckland	3C, 4C
Freyssiner New Zealand Ltd	BI	Auckland	3C

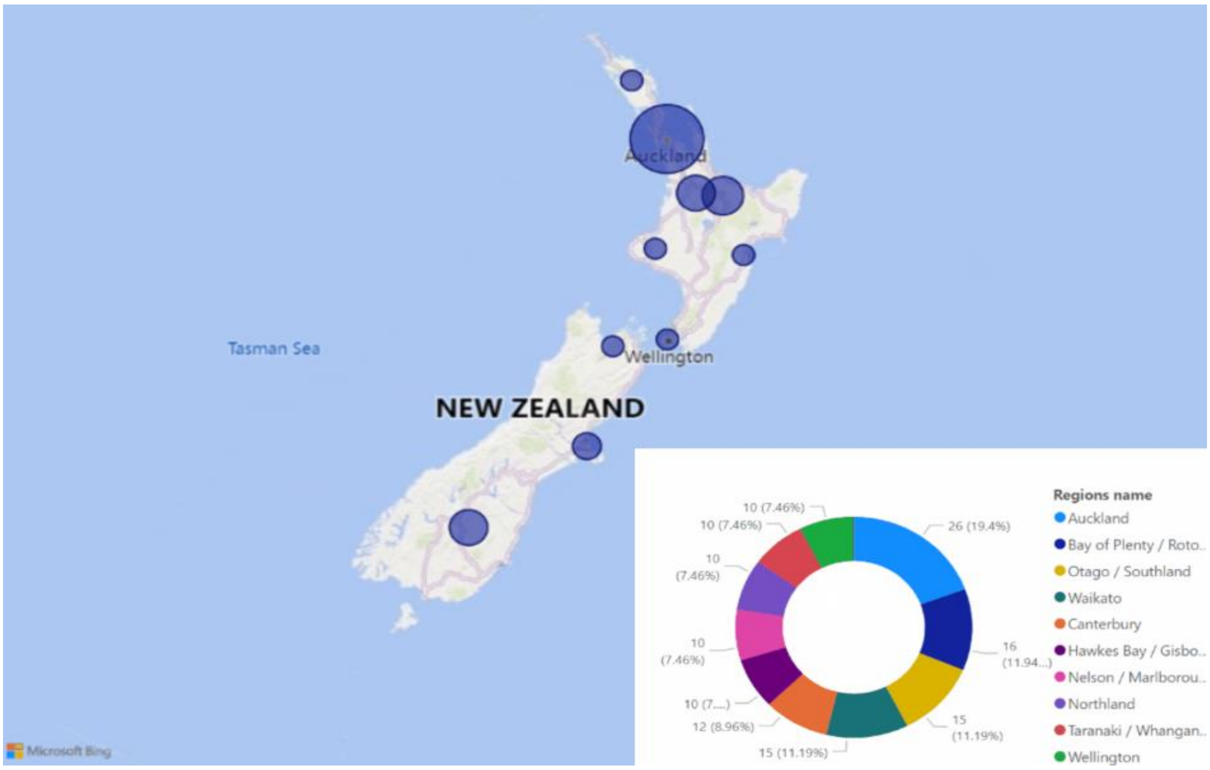
NSB Infrastructure Ltd	BI	Napier	3C
Ross Reid Contractors Limited	BI	Auckland	3C, 4B
Smith Crane & Construction Ltd	BI	Christchurch	3C
Rock Control Limited	BI	Christchurch	4C
Rooney Earthmoving Limited	SI	Timaru	1A, 4A
SouthRoads Ltd	SI	Invercargill	1A, 4B
MBD Contracting Ltd	SI	Greymouth	1B, 4B
The Isaac Construction Company Limited	SI	Christchurch	1B, 2C, 4B
Truline Civil Ltd	SI	Greymouth	1B, 4B
Westroads Ltd	SI	Hokitika	1B, 4B
Whitestone Contracting Limited	SI	Oamaru	1B
Dormer Construction Ltd	SI	Christchurch	1C, 4C
Egypt Ltd	SI	Tasman	1C
McDonough Contracting Ltd	SI	Mataura	1C, 4C
Paul Smith Earthmoving 2002 Ltd	SI	Timaru	1C, 4C
RJ Civil Construction Ltd	SI	Christchurch	1C, 4C
Te Anau Earthworks	SI	Te Anau	1C, 2C
Wilson Contractors 2003 Ltd	SI	Frankton	1C, 4C
Central Machine Hire	SI	Wanaka	1D, 4D
Contrax (Central) Ltd	SI	Cromwell	1D, 4D
Mike Edridge Contracting Ltd	SI	Rai Valley	1D, 3D, 4D
Whitestone Contracting Limited	SI	Oamaru	2B, 4B
SouthRoads Ltd	SI	Invercargill	2C
T C Nicholls Ltd	SI	Blenheim	2C, 4C
Civil Construction Limited	SI	Queenstown	4C
Tasman Civil Ltd	SI	Tasman	4C
Te Anau Earthworks	SI	Te Anau	4C

Professional service directory – Master Planning & Lead Design (MPLD) Service based on <u>new build</u> value band 1 (under $ 500,000).

- Prequalified MPLD for <u>new build</u>, value band 1, region-based map

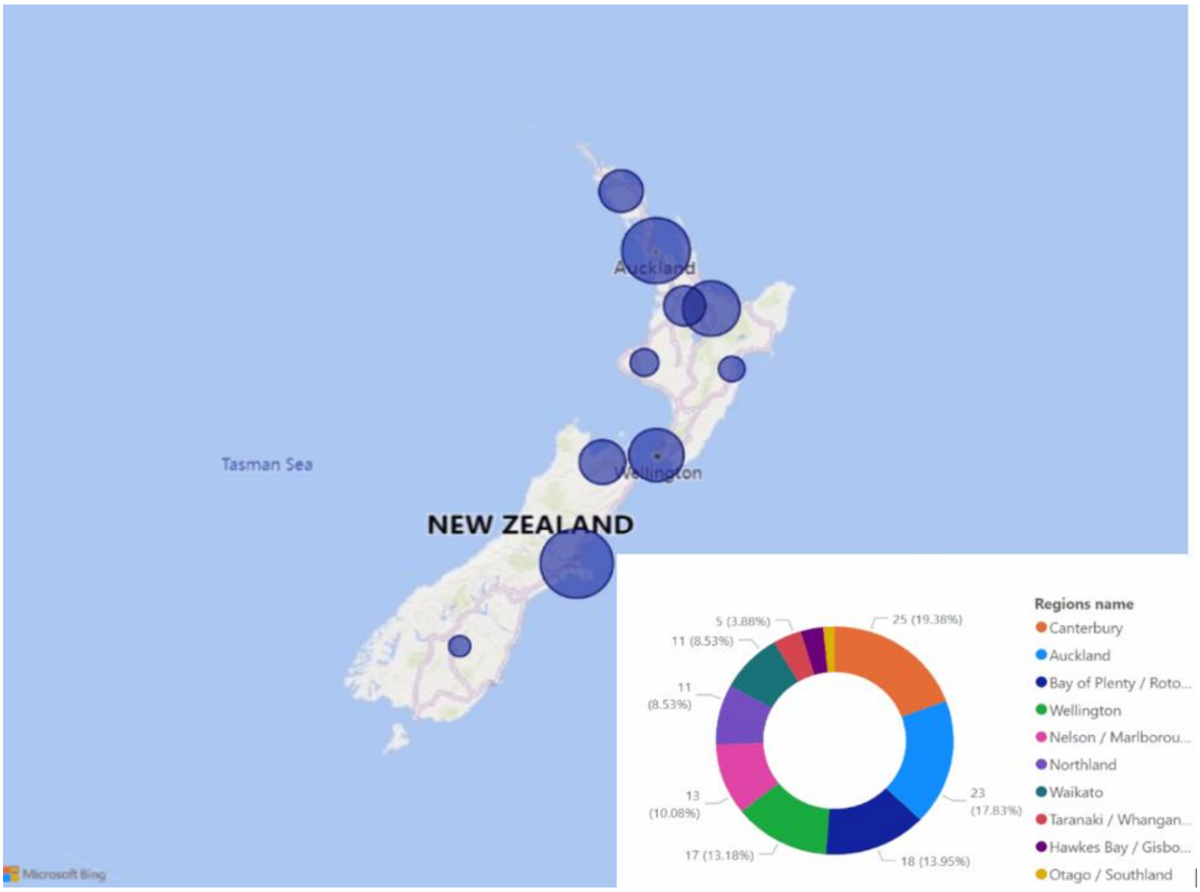


- Prequalified MPLD for <u>new build,</u> value band 1 to 6, region-based map

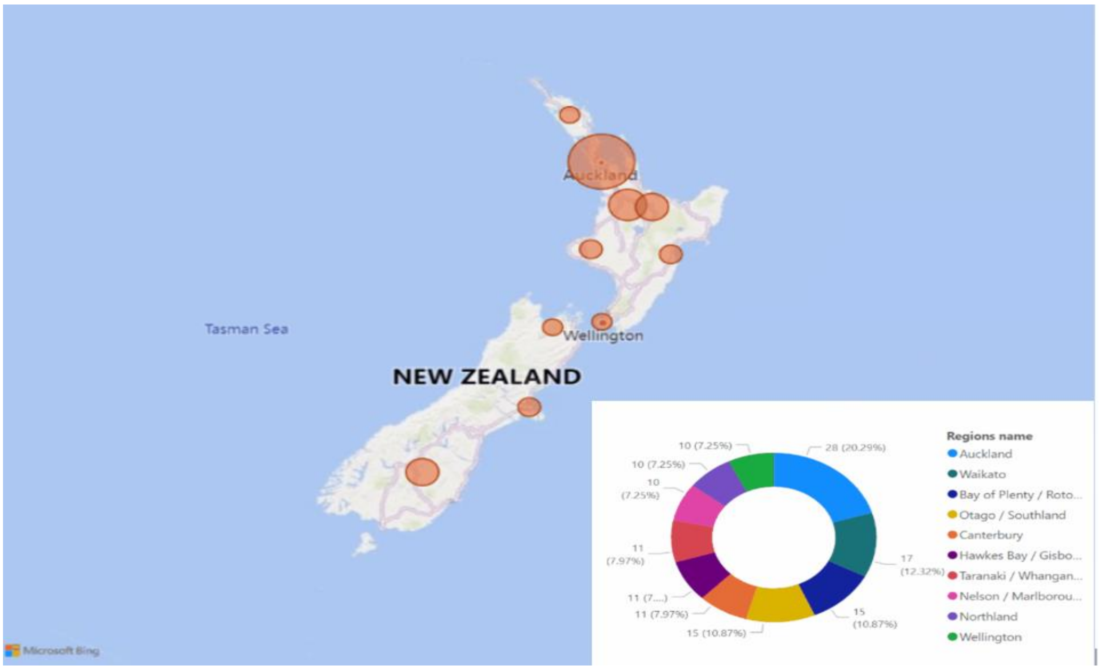


Professional service directory – Master Planning & Lead Design (MPLD) Service based on Redevelopment value band 1 (under $ 500,000).

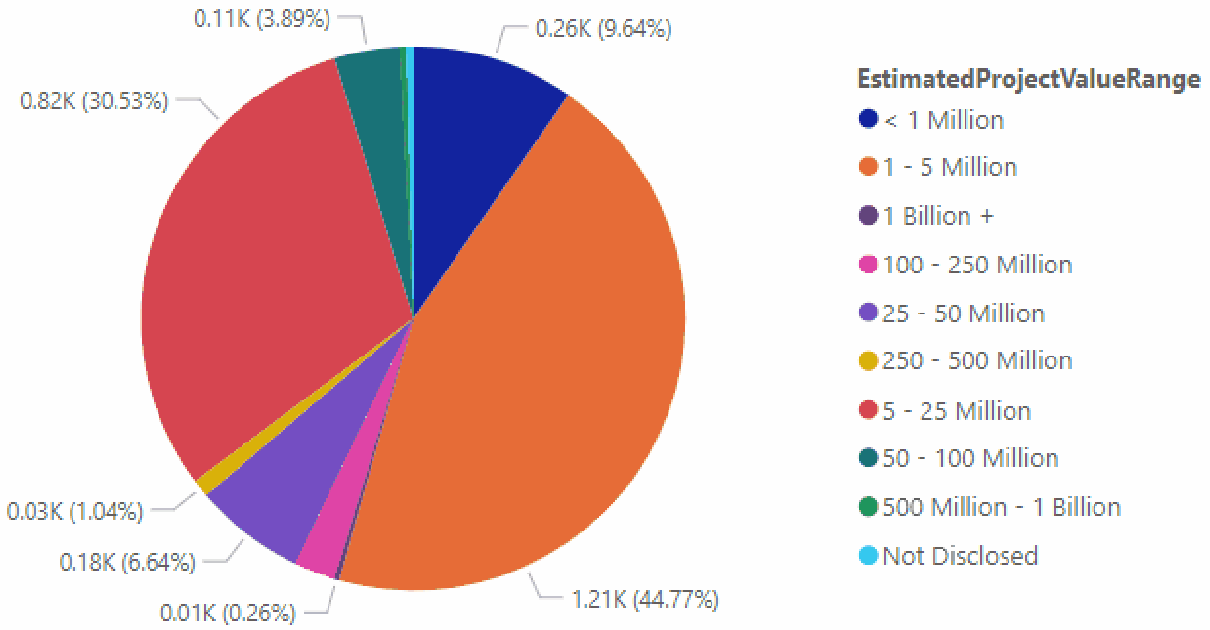
- Prequalified MPLD for Redevelopment, value band 1, region-based map



- Prequalified MPLD for Redevelopment, value band 1 to 6, region-based map

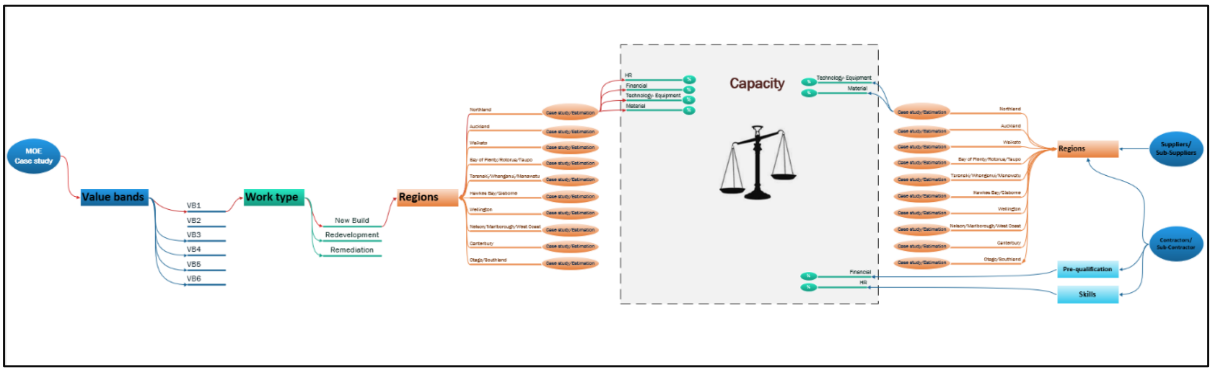


Palmerston North City Council

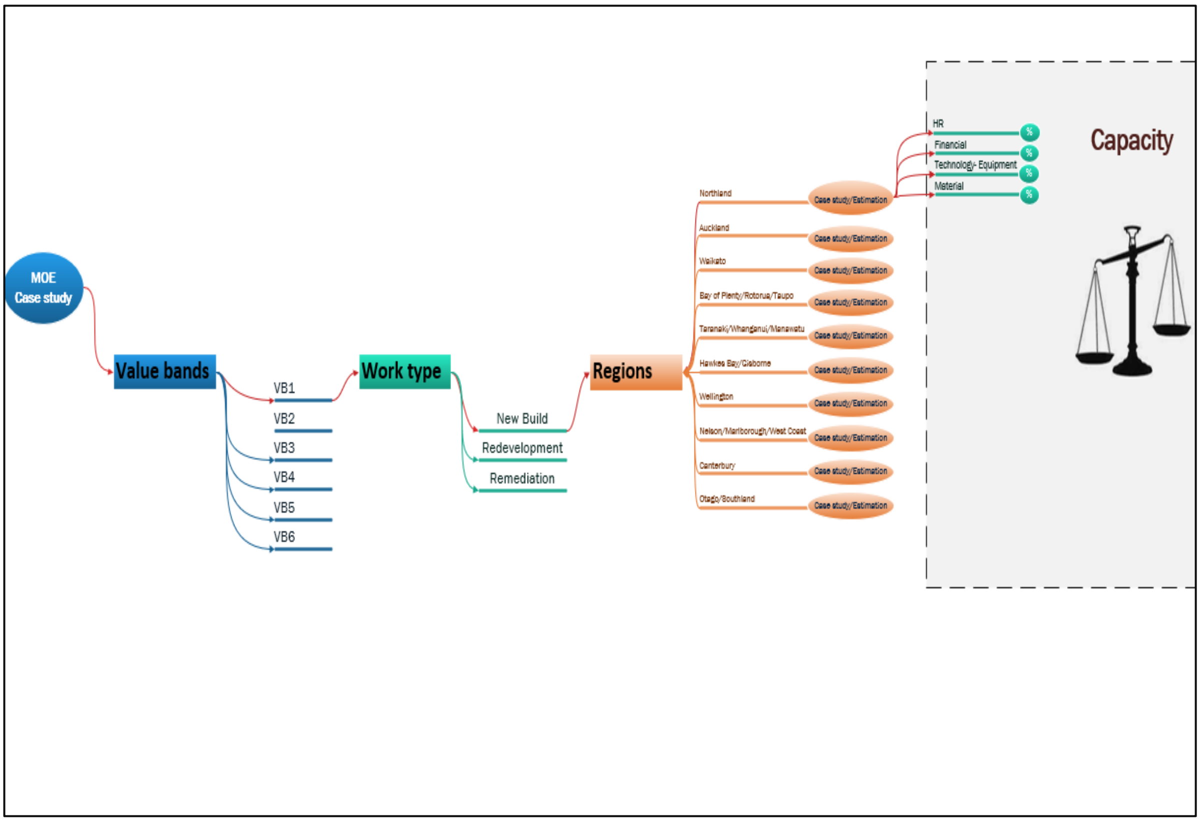


Appendix K: Capacity Modelling

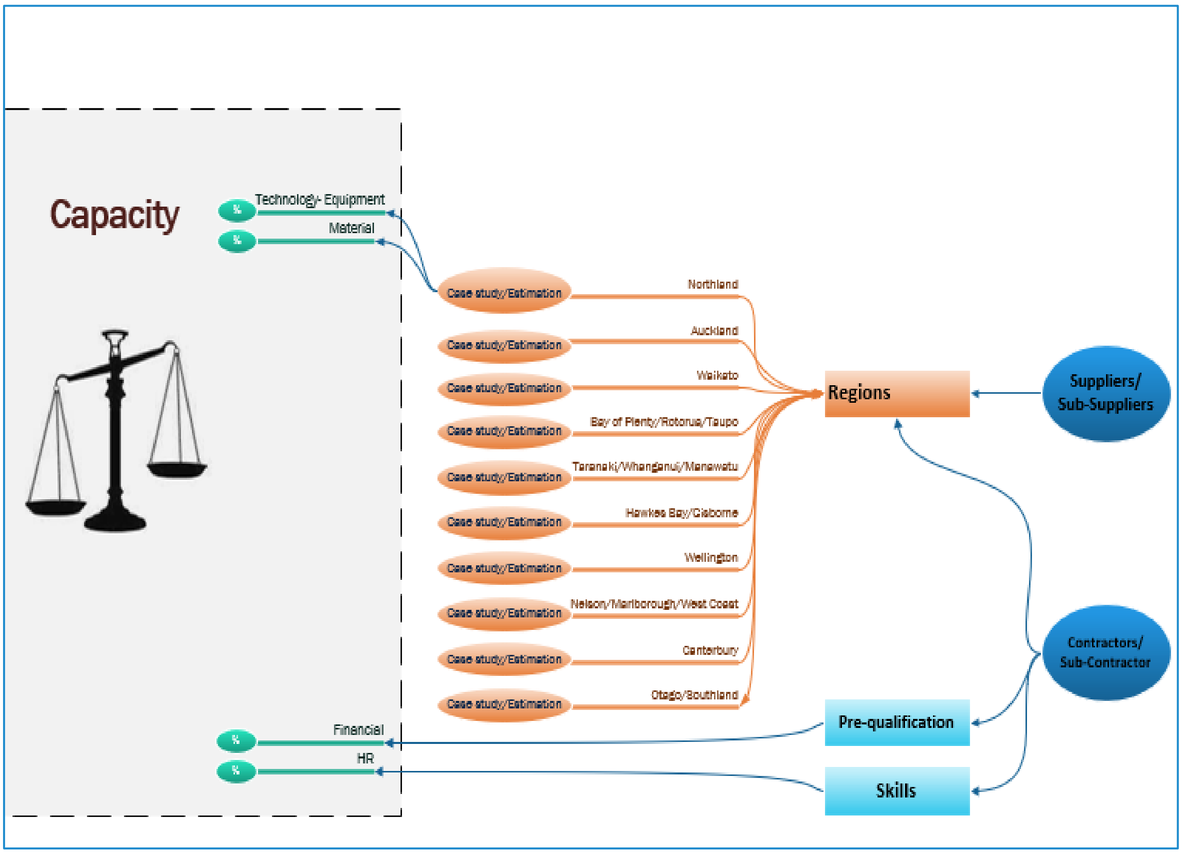
Capacity brainstorming whole model



Left side) MoE pipeline case study- the projects are divided based on value, work type and region. Then based on each case the model with the help of case study (or historical data) will estimate the capacity indicators (Human resources, Financial, Technology-equipment, Material) from pipeline side.



From the contractor and suppliers/sub-suppliers divided based on region, the model will find the mentioned capacity indicators. Then the model will compare the capacity of both sides based on regions.



Appendix L: Literature review paper for ABM

Agent-based modelling application in construction; an In-depth review and development of a conceptual model for multi-project portfolio management

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Abstract: The multi-agent systems (MAS) operations cling to the attributes and behaviours of individuals that result in final emergent configurations. Agent-based modelling (ABM) is a widespread bottom-up approach for simulating the agents, their environment and their interrelationships as components of such complex systems. On the other hand, construction projects and from a greater perspective the construction sector can be considered as a collection of MASs that include multitudes like project owners, crews, machines, supplies and suppliers, as well as diverse phases of in-progress and pipeline construction projects. These components integratively work and interact for improving the whole system's sustainability. So far, researchers have proposed Agent-based (AB) models for application in different fields involving integrated systems and also for better understanding and solving construction-related problems. The paper at hand is an effort for exploring the current argument on ABM application in construction. Considering some of the proposed models, their details and technical parts, a novel categorization of AB models is proposed. As a result, multi-project portfolio management as a less explored subject in ABM is discussed and a novel AB model is conceptualised and developed for this purpose.

Keywords: Agent-based modelling, conceptual model, construction industry, multi-agent system simulation, multi-project portfolio management.

DOI XXXXXX

1. Introduction

1.1. Why agent-based modelling in construction

Complex systems like the multi-agent systems (MAS) are identified as totalities in which the components act autonomously and result in emergents arrangements.

Simulating and predicting the behaviour of such systems is in great demand of understanding and defining its components and their relationships. Agent-based modelling (ABM) is a widespread approach for modelling, simulating, predicting and taking a step forward toward understanding such complexities. Agent-based (AB) models typically include two important components called agents and environment. These entities are artificial entities (sub-systems) that mimic real-world attributes, behaviour and interactions.

AB simulation and modelling are useful for understanding the collective behaviour of multitudes (agents) in a context (environment and applied rules for interactions) (Younes and Marzouk, 2018). In other words, each agent has distributed characters making it autonomous and a dynamic actor interacting in its shared environment (Van Dam, Nikolic and Lukszo, 2012). Agents are identifiable as self-directed individuals that are featured by sociability (recognizing others) and adaptivity (learning from experience). Agents are goal-directed which means they seek objectives and complement the configured tasks (Macal and North, 2008).

ABM as a method for modelling and simulating complex systems shows potential to be applied for solving construction-related problems. A construction project and construction industry can be perceived as a system of systems as such the interrelationship of entities (owner, employer, crew, machines, etc) impact its productivity and performance. Indeed, construction projects and on a larger scale, the construction sectors, that have multi-human or multi-organisation participants in the decision-making process can be ideal subjects for ABM. Also, "non-human-involved" or "less-human-involved" interrelationships in construction projects has many potentials to be modelled by the ABM approach; e.g. machine-machine. The construction-related multi-projects portfolio (C-MPP) can be thought of "non-human involved" subject when the projects and the allocated resources are considered as intangible individuals acting in an integrated system like ABM.

1.2. Why ABM in C-MPP management

Multiple projects that consume shared resources are handled in a multi-project portfolio (MPP) and can be subject to portfolio management for budget allocation and timing. Coming across the issue of portfolio management, an owner (also can be recognized as an organization), may face many challenges to find the best scheduling and resource allocation programs for their in-progress or pipeline projects. In other words, both complexity and uncertainty problems raise the need for [widespread] MPP planning techniques (Hans et al., 2007), while several projects with a shared and limited amount of resources shall be executed in a certain period. For example, the ministry of education of a country may have diverse construction projects of school buildings to be executed in the near or far future, but limited resources at hand. Looking at such issues from a bigger picture, the construction industry as a giant owner is in great demand of portfolio scheduling, budget allocation programming and understanding of its capabilities of consuming finite resources (Wong et al., 2010).

Allocating resources under constrained is classified by nondeterministic polynomial time (NP-hard problem), therefore heuristic algorithms may remain higher efficient in confronting MPP, rather than pure mathematical methods (Kao et al., 2006); (Abdzadeh et al., 2022). Some efforts also have been led by the researchers in applying heuristics for solving C-MPP problems. For instance, a multicriteria heuristic algorithm was proposed by Lova et al. (2000) in which the objective of minimizing the latest projects' end dates is one of the criteria for finding feasible project scheduling scenarios. Other examples are research conducted by Farshchian et al. (2017) and Farshchian and Heravi (2018) that contributed to developing a method for simulating resource allocation under different scenarios by the means of the bottom-up approach of ABM.

It has been understood that the stochastic Agent-Based simulation in portfolio management is significantly effective in cost and revenues prediction compared with deterministic approaches; the latter may lead to overestimation conditions and thus the C-MPP planning problem is more suitable to be solved by stochastic ABM (Van Dam et al., 2012). Furthermore, scheduling and resource allocation of projects are always influenced by uncertainties, therefore a dynamic modelling approach (like ABM) is required for understanding such problems (Hans et al., 2007). For example, a construction project's initial value estimation barely does remain the same until the project completion (Son and Rojas, 2011); therefore, the project value is a fluctuating project' attribute that shall be re-set through the project life cycle.

1.3. Grounding a discussion and introducing the scope of the study

Construction project resources, supply chains and the stakeholders' relationships are fluctuating over time, while the deterministic methods of system modelling are not capable of representing and involving such uncertainties in simulations. Therefore, stochastic modelling methods, like ABM, help prevent over-spending of time, cost and resources thanks to involving uncertainties and emergencies of real-world interactions in a virtual computational model. Screening the literature on ABM application in construction reveals that it is not an unfamiliar method of problem-solving by scientists in this area; so far many subjects related to construction have been tested for their adaptivity to ABM; simulating and optimizing interactions of the agents involved in the design phase, or in the supply chain of a construction project, on-site employers and crew relationships, as well as multiple machines coexistence and task conflicts were explored to be modelled through a bottom-up approach of ABM (Khodabandelu and Park, 2021; Jabri and Zayed, 2017; and Senouci et al., 2019). Also, considering the problems in the post-occupancy phase, the infrastructures and asset management as well as building evacuation and energy consumption were attractive subjects for researchers in exploring ABM applications; e.g. Osman, 2012; Hoekstra et al., 2017.

The guidelines of ABM application in construction have been discussed recently in some review articles (Araya, 2020; Khodabandelu and Park, 2021; and Xiang et al., 2021). Araya (2020) took an effort to introduce a classification based on ABM application areas in construction. It has been discussed that the AB approach has been implemented to solve site operation problems (e.g. crew interaction, and equipment planning), resource allocation complexities (e.g. multi-project portfolio budget allocation or in-progress construction resource scheduling as well as supply chain and infrastructure management). The outcome of this review article is some notes and recommendations about prospective ABM applications in construction:

- Applying ABM in construction-related models demands a good perception of entities who are to be simulated as agents.
- ABM is beneficial when the interrelationships and incorporation of system components need to be studied and the emergent outputs are expected.
- Over simplifying the real-life entities and conditions, which may have been raised from the construction projects' data access problem, is one of the limitations in applying ABM in construction.
- Validating the AB models is difficult; these models typically are externally verified based on

domain experts' opinions or comparing their outputs with deterministic methods.

The pre-mentioned barriers also are discussed in another review paper conducted by Xiang et al. (2021). They warned the researchers about the level of abstractions in AB models that may be raised due to data unavailability or computational power constraints (Xiang et al., 2021). In this article, the authors brought the MAS modelling and simulation application in construction management under the lens of critical reviewing. This article introduced the micro and macro level application of MAS (respectively in construction projects lifecycle and urban planning) and proposed a general framework for applying ABM in this research area. This framework comprises five steps including a problem statement in which the elements and environment should be extracted and abstracted. The agents then have to be the subjects of attributes and behaviour determination; also, the model objectives to be reached by the means of model emergent outputs shall be stated. The model implementation and applicability are the next steps of this framework. The introduced framework by Xiang et al. (2021) is applied as a guideline for the accomplishment of an in-depth review and grounding the discussion part of this study.

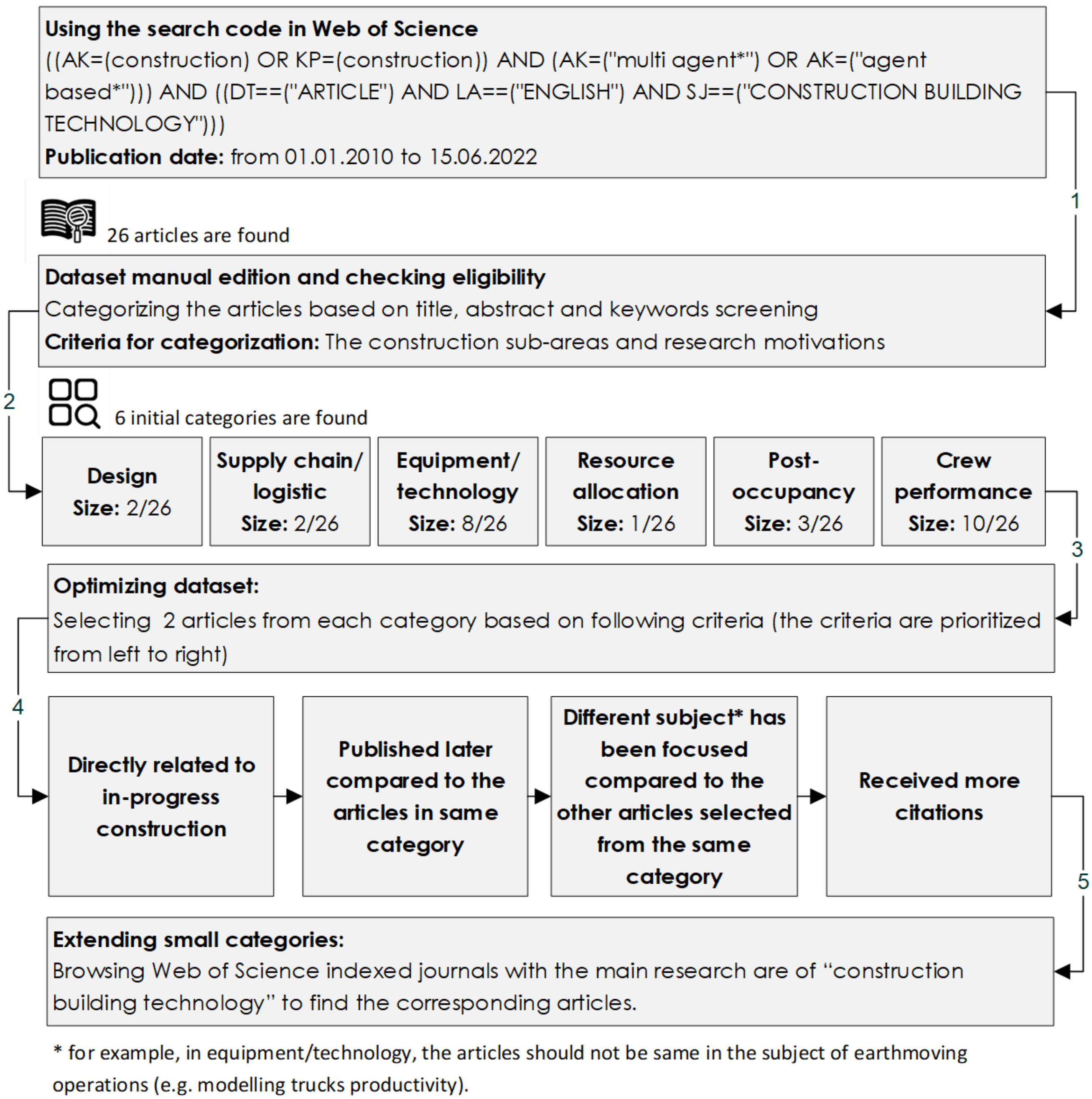

Fig. 18. Flowchart of dataset filtering and main articles selected for the in-depth review

In another recent review article by Khodabandelu and Park (2021), the authors employed a hybrid review method to analyze the content and revealed some metrics related to ABM application in construction articles. They introduced 4 major categories for applying ABM in construction phases namely pre-construction, construction, post-construction and multi-phases while each category includes sub-categories (e.g. contracts and biding, procurement, waste management, etc). In the content reviewing part, same as the other two mentioned review articles, Khodabandelu and Park (2021) was mostly intended to reveal the under-review studies' main objectives and scopes. For example, take a sub-category of the pre-construction phase namely planning and scheduling, while representative articles included in this category are Karakas et al. (2013) and Farshchian et al. (2017). The prementioned articles are placed in a single category, however, the researchers' perspective on applying ABM to the same target area (project scheduling) was different: In the former article, an AB negotiation process is modelled and the agents mimic real-world people, while in the latter article, the agents are intangible entities like a whole project with definite start, end and resource demands.

In line with previous review articles' perspectives, this study aims to introduce new categories of ABM applications in construction considering technical and model details like what is just addressed about agent types (people, projects, etc). The objectives to be reached by conducting this review paper are:

1. Understanding the agents' attributes, behaviour and space of exploration that are developed in the AB models (specific to ABM application in construction).
2. Clarifying the internal and external verification methods that have been used for AB models' evaluation.
3. Finding novel categories of ABM application in construction that are grounded on the technical parts rather than conceptual parts.
4. Finding a potential (and/or less explored) area (conceptual or technical) for extending ABM applications into that area.

2. Method

According to the main objectives of this study, a deep review of some related research articles (indexed on the Web of Science) is conducted. Accordingly, 8 journal papers are chosen in a way to cover various subject areas related to an in-progress construction project; accordingly, design and post-occupancy phases are excluded from the search criteria. Each article is then analyzed based on its scientific structure and the method of grounding the model concepts and development. Then the novel categories of dataset articles are proposed to touch on the last-mentioned objective of this paper and be the main contribution of this review paper. In the end, the findings inspired the author in developing a

Table 4. Selective articles on ABM application in construction for in-depth review.

Article citation	Title	Area of focus	Category
(Hussein et al., 2022)	Sustainable Logistics Planning in Modular Integrated Construction Using Multimethod Simulation and Taguchi Approach	Modular construction	Supply chain/logistic
(Soroor, Tarokh and Abedzadeh, 2012)	Automated bid ranking for decentralized coordination of construction logistics.	Biding system	
(Hosseinian et al., 2022)	Intelligent Stochastic Agent-Based Model for Predicting Truck Production in Construction Sites by Considering Learning Effect-	Truck production	equipment and ttechnology
(Khodabandelu, Park and Arteaga, 2020)	Crane operation planning in overlapping areas through dynamic supply selection	Tower crane scheduling	
(Farshchian and Heravi, 2018)	Probabilistic Assessment of Cost, Time, and Revenue in a Portfolio of Projects Using Stochastic Agent-Based Simulation	Multi-project portfolio management	Resource allocation
(Farshchian, Heravi and AbouRizk, 2017)	Optimizing the Owner's Scenarios for Budget Allocation in a Portfolio of Projects Using Agent-Based Simulation	Multi-project portfolio management	
(Akcay and Arditi, 2022)	Predicting Employer and Worker Responsibilities in Accidents That Involve Falls in Building Construction Sites	Consensus mechanism	Crew performance
(Raoufi and Fayek, 2021)	Hybrid fuzzy Monte Carlo agent-based modelling of workforce motivation and performance in construction	Crew performance	

conceptual model to be implemented and evaluated in future research on ABM application in construction.

2.1. Dataset collection

The outline in Fig. 1 reveals the process of the dataset collected from the Web of Science database. ABM has been given a variety of names, like Agent-based modelling and simulation, Multi-agent simulation, agent-based simulation, and multi-agent-based simulation (Khodabandelu and Park, 2021); therefore any combinations of "agent based" and "multi agent" is searched within the articles keywords. In the early stage of finding an appropriate dataset, the search code below fed the database's advanced search tool:

((AK=(construction) OR KP=(construction)) AND (AK=("multi agent") OR AK=("agent based*"))) AND ((DT==("ARTICLE") AND LA==("ENGLISH") AND SJ==("CONSTRUCTION BUILDING TECHNOLOGY")))*

The search code represents that the journal research articles (DT==) with the main language of English (LA==) are filtered according to the following main considerations:

- the words "multi agent" and "agent based" and the variations like agent-based modelling, multi agent systems, etc. should be provided as author keywords (AK=);
- the word "construction" should be mentioned among the author keyword or keyword plus word list (AK= & KP=);
- and the publications should be categorized under the Web of Science research area (SJ==) of "construction building technology".

The search result then is filtered to include the papers published within a timespan of early 2010 to mid of Jun 2022. The early obtained dataset includes 26 articles that have been subjects of title and abstract screening for further manual dataset pruning. It is observed that the articles can be initially categorized according to the main contexts of exploration and construction sub-areas:

1. Design;
2. post-occupancy;
3. supply chain/logistic;
4. equipment/technology;
5. resource allocation;
6. and crew performance

It is aimed to widen the outlook of this review article and cover a diversity of previous subjects that attract researchers to testing ABM applicability in construction. Therefore, except for the two first categories ("design" and "post-occupancy"), the final dataset includes two papers related to the different in-progress construction phases for each category. Table 1 lists the selective articles for further in-depth reviewing. It has been tried that the selective papers in each category cover various subjects, however, the "resource allocation" category in this list is an exception; due to the rare paper focusing on ABM application in resource allocation, the two selective articles focused on the same subject of multi-project portfolio management.

2.2. In-depth review criteria determination

The main objectives that have been mentioned in the introduction section, are pursued by answering relevant questions about each article; Table 2 is a sample table that is filled for each dataset article during the process of reviewing. This method of reviewing is also helpful in articles' categorization based on technical considerations. For example, having understood what entities in the real world are artificially presented in AB models, some categories may be revealed according to the type of model components, e.g. human agents, conceptual agents (like projects or activities), geography-inspired environment, conceptual environment (e.g. project portfolios). The following clarifies the review's criteria.

Agents and the components in an AB model can be classified as unique entities with particular attributes, systematic behaviour, desires and objectives; in other words, the agents can be coded as classes. Defining the agents, their attributes and developing their classes is a critical step in ABM; raw 3 of Table 2 targets this issue. Also in an AB Model, autonomous agents explore a given environment for self-interest (Du, El-Gafy and Lama, 2016) which is also pointed out in raw 3 and 4. The prementioned characteristic make the model definable via object-oriented programming and some software are developed to be implemented by researchers as user-friendly programming tools; this criterion as the internal verification method is addressed in the raw 5. On the other hand, the methods for exploring real-world applicability and actual model performance evaluation are to be mentioned in raw 6.

Table 5. Sample table to be filled for each dataset article

	Article title
1	Motivation and context
2	Research significance
3	Agents (attributes and behaviours)
4	Exploration space
5	Software implementation/internal verification
6	External verification method

3. Findings

The review guideline sample table (Table 2) is filled for each dataset article (Table 1) and the results are mentioned in this section. According to the findings of agent attributes and model details proposed in each article, they could be categorized based on some technical consideration. Fig. 2 introduces novel categories made out of the same review articles in Table 1. In the pre-mentioned figure, the agent means an autonomous actor with recognizable attributes and behaviour, while the space of exploration means the area with limited degrees of freedom which is recognizable by the agents; the agents are placed in (circumscribed by) this area and are allowed to explore this space to reach their objectives.

The model proposed in each article has a specific perspective to create artificial agents and their environment scenarios. The agents are tangible in every model which means they are recognizable by the users through particular attributes, behaviour and aims. Such tangible agents mimic either real-world tangible entities, like humans and machines, or real-world intangible entities like projects and activities. Moreover, the agents' environments or in other words, the space for agents' exploration, can be an intangible exploration space like a set of rules and equations (e.g. rules that lead the process of negotiation between construction crews), or an illustrative coordinate system with figurative dimensions; the latter, as tangible exploration space, can either mimic geographical locations or real-world intangible borders. Having Fig. 2 in mind, in the following sections, the findings based on 8 reviewed articles are denoted.

3.1. Real-world intangible entities as autonomous agents

The challenge in construction supplier selection motivates Soroor et al. (2012) to model a single product supply chain for automating such a process. They focused on the costumers' roles and design specifications in a bidding system where they integrated agent-based modelling and fuzzy logic through a hybrid algorithm. In this study, a supplier evaluation agent was fully designed as an automated decision-maker engine. It received the inputs as customer demands and design specifications and then employs decision matrixes to rank a set of suppliers. This model focused on a sub-system within a complex system of the construction supply chain. Therefore, this sub-system can be classified as a real-world intangible entity that acts in its tangible environment (a single product supply chain) as an intelligent decision-maker. This agent was individually developed and no space of exploration can be specified. In other words, there were no rules introduced for agents' interrelationships in this study except for the restriction received (by the supplier evaluation agent) via the customer suggestion and design specification.

In another study that considered real-world intangible entities, Farshchian et al. (2017) model portfolio projects as the agents act in a MAS. Some inputs determining the project agents' classes were the physical planes of each project, cost flow, project outcome after completion, etc. As the critical issue of budget limitation causes the elimination and postponing of some projects, a model was developed to help financial management of several ongoing construction projects in a portfolio for lowering project costs and delays. The model was implemented for simulating and predicting construction projects' progress (with a limited budget) or revealing the efficient budget allocation scenarios within an owner's portfolio (with a given physical progress plan). In the first scenario, the project's progress plan was estimated based on the limited budget fed to the model (i.e. the costs of the projects were entered into the model). In the physical progress scenario, the model evaluates the cumulative budget needed for the realization of the planned physical progress (i.e. the physical progress plans of projects were entered into the

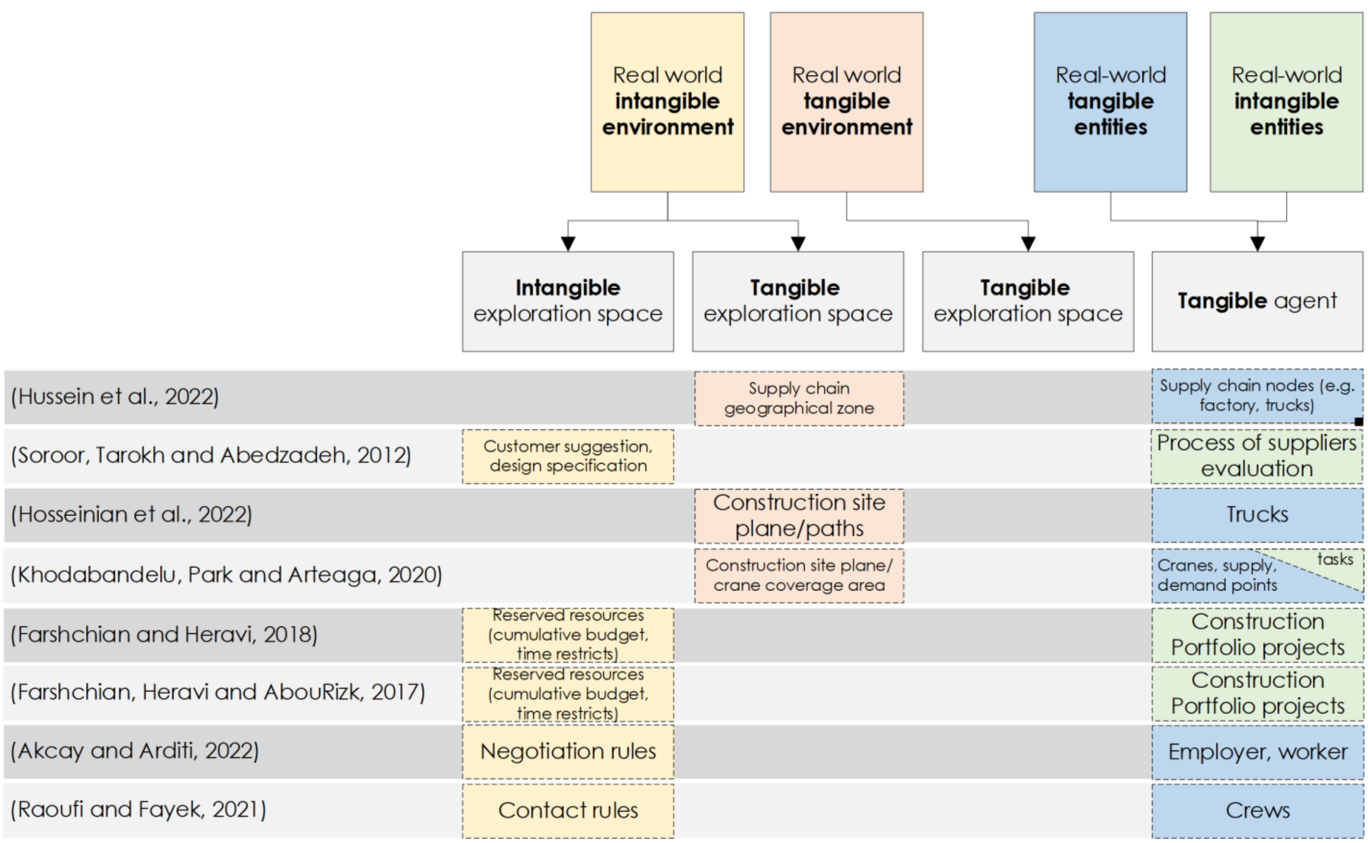

Fig. 2. *Re-categorizing the dataset articles based on AB models' details*

model). Moreover, in an extra scenario, namely the optimization scenario, the objectives of maximizing the cumulative projects' outcome, and maximizing the cumulative number of completed projects were targeted; the model suggests the best cost and time schedules based on different projects prioritization setups.

Moreover, the same authors later proposed another model for multi-project portfolio management namely stochastic AB simulation for cost, time and revenue assessment (Farshchian and Heravi, 2018)). Like the earlier study, the model simulates two types of scenarios: project progress and budget allocation. However, in contrast with the earliest model in which the deterministic data of each project's cumulative cost and physical progress were fed to the model, the latest model used stochastic data (randomly selected from inputs); accordingly, it provided probabilistic outputs.

3.2. Real-world tangible entities as autonomous agents

On-site equipment is real-world tangible entities and is distributed on the site plane characterized by certain location information. With the same viewpoint, Khodabandelu et al. (2020) developed an AB model for tower cranes task conflicts recognition and scheduling operation. They introduced two types of dynamic (crane) and static agents (supply and demand point); it is worth mentioning that this article took a hybrid approach in defining agents as the task agent (real-world intangible entity) was introduced as a dynamic model component with particular attributes. The article brought an argument to the literature on cranes' task scheduling where minimizing an individual task's execution time was not superior anymore; instead, they focused on cumulative time minimization with considering tasks' collision. The main aim of ABM in this research was to find the most effective crane-supply point connection for each task.

Except for cranes, the trucks were also modelled as the construction site equipment agents in an AB model of truck production. Integrating trucks' learnability into an AB model, Hosseinian et al. (2022) developed a model of truck operation aiming for finding minimum travel time (supply to demand point travel). Moreover, the model was fed by stochastic data to understand the impact of uncertainty related to fuel level and traffic congestion on the multiple trucks' performances. Their model includes trucks as intelligent agents, their class of behaviour (travelling from point A to B), and the environment (construction site as a real-world tangible environment). The agents receive environmental interactions based on a reward/penalty framework; The reward increased when the travel time decreased. Two scenarios were suitable, one considering the effect of traffic volume and the other considering the traffic simultaneously with fuel level.

Other types of real-world tangible agents are human agents who can be easily classified according to their desires, duties, personal characteristics and behaviours. Considering the employer and construction crew negotiations, Akcay and Arditi (2022) proposed an AB model that helps the process of consensus among the parties. This model included two agents (employer and worker) participating in an automated negotiation about the onsite accident responsibilities. The ontology behind agents and rules development was based on court data, expert domain ideas and surveying with the Delphi method. The Zeuthen strategy was employed as a settlement protocol where in each iteration, the two agents were evaluated based on their risk tolerance.

Moreover, the crew were the main focus of other study conducted by Raoufi and Fayek (2021). They developed a hybrid simulation method, where Fuzzy logic, Mone Carlo and ABM were integrated. This model was developed for simulating crews' contact while they got influenced by each other and their motivation changed. The crew's mentality is an intangible real-world environment and was developed as an intangible space of exploration in this model. This model restricted the agents to influence (or get influence) from the environment by the means of an equation; that equation calculated crew motivation and included contact rate, agent type (zealot/non-zealot), susceptibility, etc.

From a novel perspective of simulating heterogeneous real-world tangible entities, Hussein et al. (2022) developed a multimode model (including ABM and discrete event modelling) of construction projects distributed supply chain. The dynamic environment of a logistic system was modelled where the factory, trucks, customer clearance, storage area and construction sites were the model components. The model simulated a geographically distributed supply chain and depicted the interrelationship among the agents; it is used for analysing the impacts of critical decisions made by the autonomous agents on the total supply chain cost, project duration and carbon emission.

3.3. Methods of evaluation and implementation of AB models

Developing an automated bidding system, Soroor et al. (2012) verified their model's applicability by testing it in a case study when 4 suppliers are to be ranked and selected. The applicability of such a biding system was claimed to be true with prioritizing the fuzzy logic over crisp ranking. Another article that adopted a case study as a method of internal verification was Farshchian and Heravi (2018); they demonstrated the AB model performance with 50 project agents and compared the outcomes of the stochastic model to a deterministic one; where the AB model showed higher capability in predicting cost and revenue.

The case study is a widespread method of internal validation of AB models as it was also employed by Khodabandelu et al. (2020). They ran the model based on the information from a peak day of a construction project; it includes 3 cranes responsible for executing 21 tasks and the different scenarios (13,824 combinations of tasks allocated to various cranes) were simulated. They compared the outcome of their proposed model with the outcomes of conventional methods when ABM was proven to provide efficient crane operation timing in executing certain tasks. A Java platform is used for developing and implementing this model as it is claimed to be compatible with ABM (since it is object-oriented) and well suited for modelling complexities. Other models are also implemented by Java as an agent development tool like the negotiation model proposed by

Akcay and Arditi (2022). However, Java was not the only tool for ABM and MATLAB was chosen for model implementation in Hosseinian et al. (2022)'s work.

software as a tool for model implementation. This study denoted the methods of internal and external verification through 6 steps. First, the extreme value, relative value and

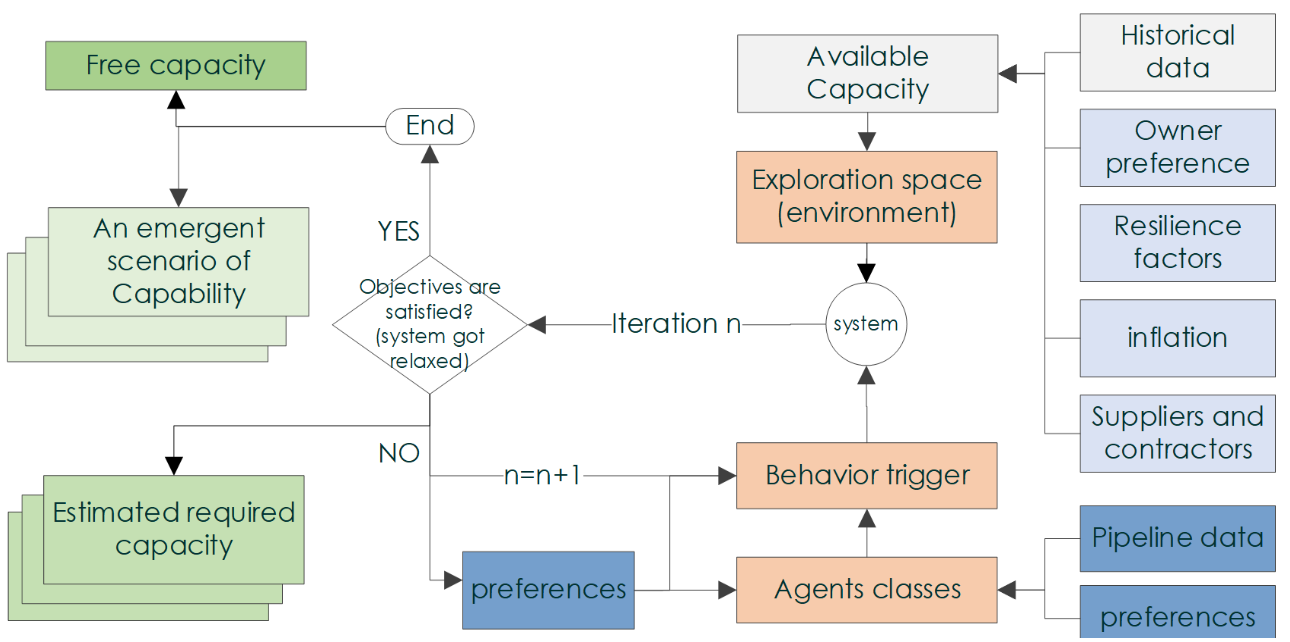

Fig. 4. The conceptual model developed for exploring organizations' capacity and capability for/of delivering pipeline project

random samples fed the model to test its performance. Then, three steps of macro-face, cross-validation (comparing to other methods) and real-world data validation were taken to evaluate its applicability. It is proven that the model helps increase logistic system sustainability by providing a better understanding of its operation and the impacts of the decisions on the key performance indicators (cost, time, etc); e.g. inventory decisions or truck selection.

To verify the model proposed by Hosseinian et al. (2022) for truck production, the authors compared a case study simulation result with the results of traditional methods of project planning namely Mone Carlo-critical path; The mentioned logic was used for finding the shortest travel path from a set of given paths, while the AB model proposed showed more applicabilities (e.g. proposing shorter travelling time for trucks with higher probability). Also, the model is externally verified through a comparison between model results with the results calculated by hand; this verification was based on a simple artificial case.

The model of crews' contacting developed by Raoufi and Fayek (2020) was also verified by implementing a real-world case study. However, the method of evaluation was limited to sensitivity analysis and conceptual validity check. It is concluded that increasing the number of highly motivated crews at the first step, improved the crews' cumulative performance.

Except for comparing the model output with conventional models output, using historical data is seen to be a more reliable method of model evaluation. Akcay and Arditi (2022) compared the outcome of their AB model, as an automatic negotiation, to the historical data provided by courts. Another example of using historical data for model validation was what Farshchian et al. (2017) conducted; they proved that their model can simulate the real samples of construction projects' progress exact as their actual progress (99.99%).

The last article to be mentioned in this section is what was conducted by Hussein et al. (2022). They used AnyLogic

4. Discussion

Using a figurative coordination system as the agents' environment, makes the real-world intangible entities to be more understood. It is beyond dispute that the systems' operations are more clear through figurative illustrations and presentations. In what follows, a conceptual model has been proposed in which the portfolio's construction projects as real-world intangible entities explore an artificial coordinate system. Indeed, the agents' exploration space is developed like a semi-2d environment mimicking the portfolio owner's reserved (available) capacity and resources (as a real-world intangible environment) (Fig. 3). This conceptual model is useful for assessing the projects owners (individuals, contractors, organization or industry) reserved capacity, estimating required resources and capability.

This conceptual model is original in terms of integrating the simulation and visualization of the real-world intangible entities by the means of ABM and figurative displays. What is proposed is to be a step forward for extending the body of knowledge in ABM application in C-MPP management and motivating prospective researchers.

4.1. conceptual ABM development

ABM application in C-MPP management is the main concern of the conceptual model developed in this study. In this AB model, agents are the pipeline projects as real-world intangible entities and their environment is a semi-2d coordinate system as a tangible exploration space that mimics a real-world intangible environment (refer to Fig. 2). In the proposed model the agents explore for the best collective configurations or (near)optimized emergent out-layers within a semi-2d coordinate system. This conceptual model is original in terms of illustrating the real-world intangible entities in a figurative and tangible exploration space. Also, it is significant in representing a portfolio owner's capacity as such to be illustratable via an artificial coordinate system. More details of the model inputs, settlement protocols and potential outputs are discussed further in the next sections.

Each project can be considered a temporary endeavour undertaken to create a unique product with a definite beginning and end (Farshchian and Heravi, 2018; and PMI (Project Management Institute), 2013). However, according to the results of screening various datasets of organizational pipelines of construction projects, some other potentials and limitations are found regarding individual projects. For example, it is understood that along with the starting and end date, the value bands or estimations of the total budget that is required for project execution should be provided. These are the minimum information required about the construction projects to be considered as pipeline projects. Besides, referring to an organization's construction projects' pipeline, the categories of project types, like new buildings, re-development, etc. should be found. The prementioned data about each project is what feeds the model as inputs that make the basis of the model agents classes and enable available capacity estimation.

Fig. 4 demonstrates the conceptual model outline. The capacity is obtained by historical data analysis and can be manipulated according to external factors like inflation rate, resilience factors (earthquake, ware, etc), or the details provided by the owner. The capacity is then quantified and makes the basis of agents' space of exploration. On the other side, the agents' classes and behaviour are defined based on available pipeline data and user preferences.

In an AB model each time that the system runs it is called one iteration. In each iteration, the agents pass an act to explore the space aligned with their objectives. At the end of each iteration, the agents find a cumulative configuration in their environment. The very first configuration at iteration 0 is to be set by the user. Based on the attributes, behaviour and objectives, the agents then explore the space for better configurations through the next iterations. Moreover, based on the initial setting and the objective prioritization, the emergent outputs, as relaxed collective configurations can be varied. As AB Models outputs are intrinsically near-optimum solutions, the best collective configuration in each scenario is an emergent cumulative agents' layout that is obtained at the end of an iteration where no re-configuration occurs in the next iteration (system gets relaxed). Therefore as Fig. 4 clarifies, if the system gets relaxed, the system stops operating and introduces a scenario of portfolio configuration. On the other hand, in each iteration, when the system does not find a

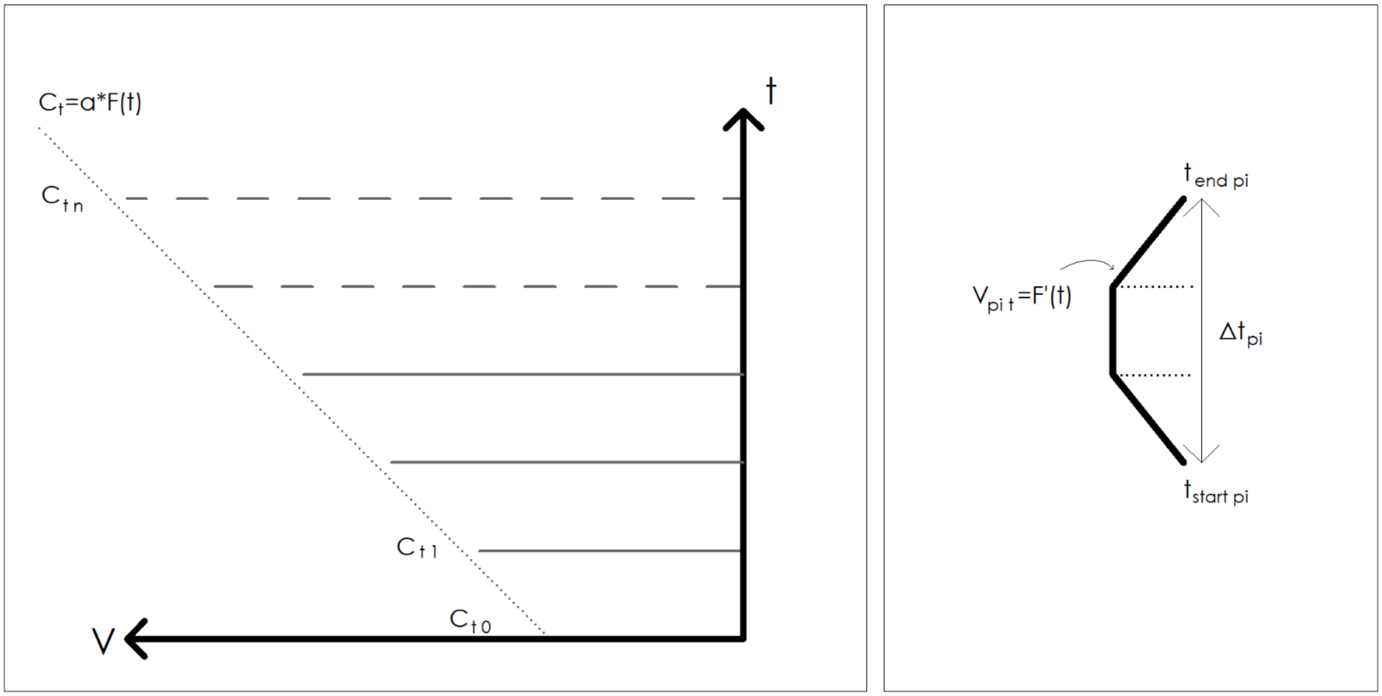

Fig. 5. left) agents' space of exploration (environment); right) project agent *i* and its attributes

relaxed configuration, it estimates the required capacity; the required capacity equals in-demand resources (extended available capacity).

The environment that surrounded the agents and circumscribes their exploration, is a semi-2d coordinate system mimicking the portfolio owners' reserved capacity (available resources). The dimensions that determine this semi-2d coordinate system are labelled as value interval (V) and time interval (T). The figurative illustration of the environment is shown in Fig. 5; left. The environment is the agents' tangible space of exploration and it is named a semi-2d environment since the V dimension is not fixed in terms of time.

In Fig. 5, C_t is the reserved capacity at time t where the float number a is the capacity changing rate. The capacity and the changing rate of a are obtainable by analyzing historical data. For example, screening the completed projects by the owner in the years 2018, 2019, 2020, and 2021, and according to the attributes of the in-progress projects at that time (start and end dates, total value and resource consumption equation), the capacity is calculatable for the pre-mentioned years; the summation of distributed projects values (all the allocated budget) at that particular year. Therefore, for t as a period in past, the $F(t)$ is calculated as Equation (1) denotes:

$$F(t) = Sum\, Vpx_{\ t} \quad (1)$$

Where $x \in 0 \ldots m\}$ and m are the number of in-progress projects at time t; $F(t)$ is available capacity at time t; and Vpx_t is a function that calculates the project px value at time t.

It is assumed that the value is distributed or in other words, the budget allocation for the project is distributed through a time interval of Δt (where $\Delta t = t_{end} - t_{start}$). The value distribution is assessed by a distributed value function (consumption function $F'(t)$ for each project) that is fed to the system as an input. As illustrated in Fig. 5; right and Fig. 6, the attributes of each agent determine its figure or body shape. The class of agents' attributes (Agents.Attribute()) that directly influences their body shape includes:

1. Start_t: beginning time
2. End_t: completing time
3. Value: total value estimated
4. Consumption function: can be inserted as a function, or be set as a default

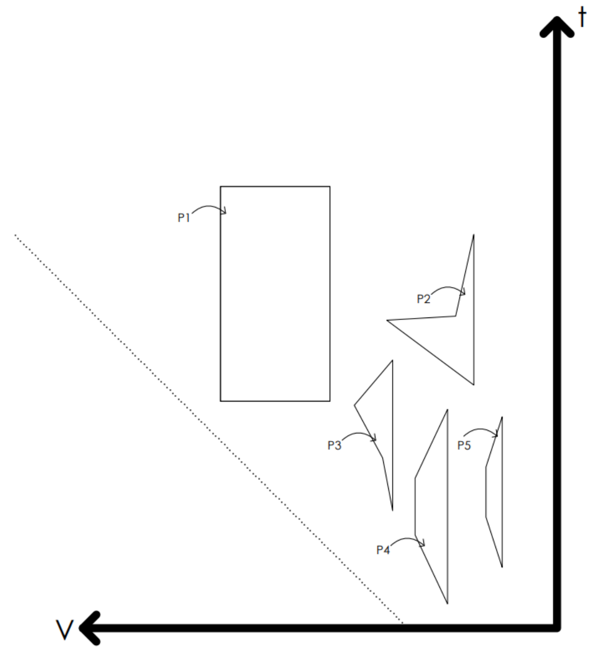

Fig. 6. Sample agents *p1* to *p5* while space exploration

Also, the protocols that determine the agents' actions are characterized by their behaviours. The triggered behaviour of the agent leads to input data manipulation by the given and allowed rate; the agent behaviour class includes:

1. Move_t: move along t direction is enabled.
2. Trigger_ Δt (N): duration change is enabled and is fluctuating by +/-N % where N is a float number in the interval (0, 100).
3. Trigger_consumption (N): consumption rate is not fixed anymore and +/-N% change is applied where N is a float number in the interval (0, 100).
4. Prioritize (l, s): the agent got level l priority by s for strength.

For a better understanding of an agent's behaviours, its objective that is desired through space exploration shall be recognized. For example, the Move_t behaviour enables the agents to shift between different time stamps (change the starting date); this ability helps the agent reach the objective of finding the best start point where the consumption function, total value and the duration remain as same as early inputs. Moreover, the agents are aware of each other's attributes and real-time locations; this means that they, as an inter-related group, seek a relaxed collective configuration in which the desires of individuals are satisfied. Accordingly, when the Trigger_ Δt (N) is enabled, the agents are given a degree of freedom to change the duration (*Δt)* to some extent (N%); such flexibility is required when the agents can't settle down and produced a relaxed collective configuration. Fig. 7 shows the settlement flowchart to be followed by the agent i.

In the proposed conceptual model, the operation starts with a collective configuration driven by pipeline data (iteration 0). The pipeline data, as a datasheet provided by the owner of C-MPP, determine one collective configuration that is not usually evaluated for its practicality; therefore, the owner's pipeline scenario is predicted to be compatible with an over or less estimation of the owner's capacity and produce an unrelaxed state. However, autonomy, reactivity, mobility, sociability and rationality are the properties of a MAS; It means the prominent objective of each agent in an AB model is to explore the space for learning and making advances through experience (Soroor et al., 2012). Indeed, the agents act and interact in a dynamic environment and learn based on trial-error mechanisms (Hosseinian et al., 2022). In the proposed model, once a behaviour is triggered, the agents play with the parameters, compare their progress to the last iteration, and continue progression until the whole system gets relaxed.

Moreover, as the ABM developers agreed that the AB model's verification is not easy and limited to a few techniques, the method of verifying this model can be either based on historical data or based on domain experts' opinions. The model can be implemented using object-oriented programming languages like python. Since a platform for graphical visualization is also needed in further steps, the programming platform should be available for bridging it into 3d (or 2d) modelling software.

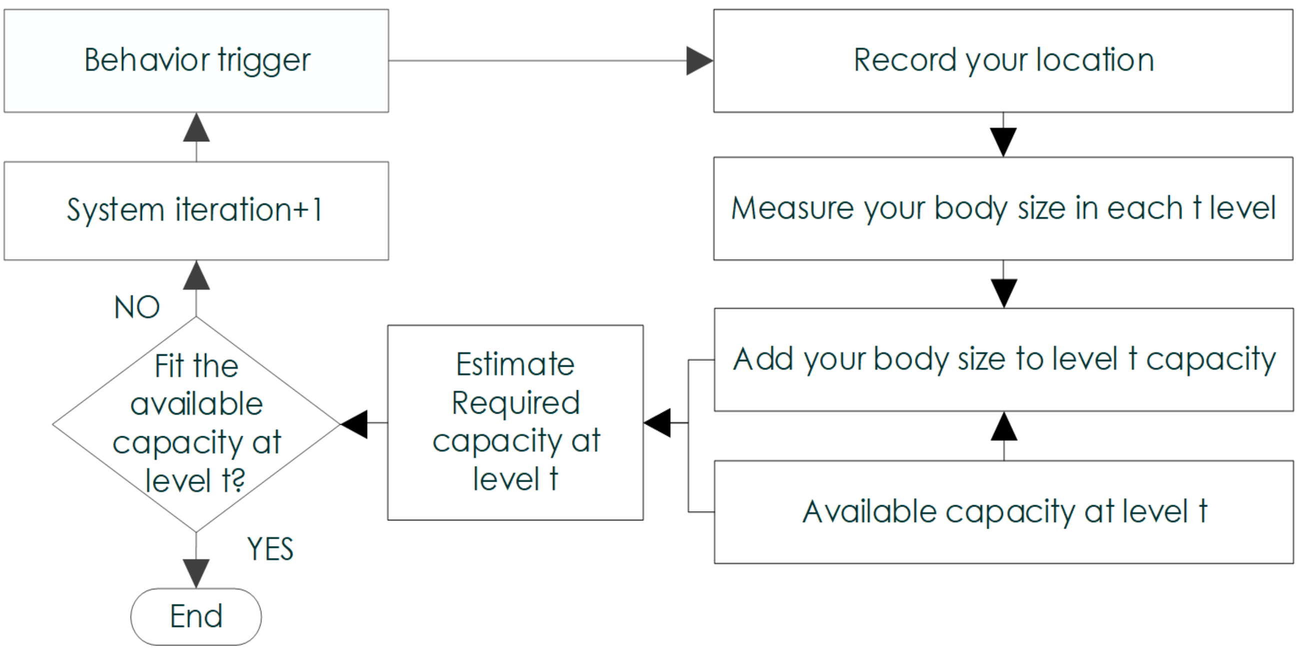

Fig.7. Settlement protocol outline

5. Conclusion

ABM is a widespread method in modelling and simulation complex systems. The construction sector with its complex nature was also the subject of ABM and AB simulating. The aims of conducting this paper were to find the details of AB models' components, and methods of AB models' evaluation, and to take a technical perspective on the issue of ABM application in construction. These targets have been touched through the following steps: First) a dataset of newly published journal articles related to ABM application in construction was collected and it was tried to cover diverse focus areas. Second) An in-depth review of developed models' technical considerations was conducted (guided by ABM standard protocols).

The in-depth technical considerations helped envisage a novel category of AB models based on the model components' origins; accordingly, the real-world tangible/intangible agents were found to be always simulated as tangible agents that are recognizable by special classes of attributes, and behaviours and objectives. The agents' space of exploration (simulated environment), on the other hand, can be either tangible (like simulated geographical locations) or intangible (like a set of circumscribing rules). The under-review articles were classified according to these attentions.

Along with AB models' details, the methods of ABM verification were also revealed. Case studies (based on either real-world data or artificial data) were the most common method of internal verification of AB models. The common external evaluation method, to prove the proposed models' applicabilities, was comparing the result of simulations with the traditional models' outcomes; for example, deterministic simulations, Monte Carlo logic or even the result of manual calculations. On the other hand, despite the construction-related data access problems, comparing the AB models' outcomes with the actual real-world information (projects' historical data) was recognized as another possible method of evaluation.

Moreover, the model implementation tools were recognized to be mostly based on object-oriented programming platforms (e.g. Java or MATLAB). The AnyLogic software was also found as a useful tool in agents' classes' determination and graphically simulation of AB models.

The findings motived the authors of this study to propose an AB model as a technique for understanding a less explored area; i.e. ABM application in C-MPP management and illustrating intangible entities in a tangible exploration space. The model discussed is an early-stage model for exploring a project portfolio owner's capabilities in resource allocation and pipeline project scheduling as well as estimating the required capacity for on-time/by schedule project delivery. The conceptual model introduced in the discussion section is significant in terms of modelling real-world intangible entities as agents that act in a virtual coordinate system. The semi-2d coordinate system proposed in this model is representative of a real-world intangible environment (where the portfolio's owner's available capacity is visualized).

This model is considered to be a guideline for researchers who may be interested in applying ABM in C-MPP management. The future research focus can be on 1) Implementing the proposed conceptual ABM model for internal and external verifications; 2) Creating a cloud database for sharing projects agents classes and contributing it to the broad realm of portfolio management; 3) working on simulating and integrating the geographical locations as representatives of the real-world regional resources to improve the model performance in practice.

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Appendix M: Agent Based Modelling processes, requirements future advances

Class definition code and request for information

The prementioned data about each project is what feeds the model as inputs that make the basis of the model agents' classes and enable available capacity estimation. What follows is the initial project agent class definition:

```
class project_agent:

       def __init__(self, start, end, region, type, group, value, value_distribution):

        self.start=start # The "start" and "end" refers to the project start and end date with the format yyyy OR QQ-yyyy

        self.end=end

        self.region=region  # The location of the projects should be defined based on three main regions: South island=1, south of north island=2, and north of north island=3.

        self.type=type  # The project type is either horizontal (=1) or vertical (=2).

        self.group = group #  The project group refers to the project's main function (e.g. school, hospital, road, etc) and should be set as a string.

        self.value=value # total value in M$

        self.value_distribution=value_distribution # The value attribute considers N million dollars, where N is a positive float number, e,g. 5 M$. Value_distribution is a set of numbers. Each item included in this attribute should be considered as n% for each time step (each year during project execution); e.g. for 5 years of duration, the value distribution sets can be [5,25,60,5,5] while the sum of the set items equals 100. It also can leave empty to be considered a homogeneous distribution).

        self.duration=self.end-self.start
```

On the other hand, the environment that surrounded the agents and circumscribes their exploration in space, is a semi-2d coordinate system mimicking the portfolio owners' reserved capacity (available resources). the contractors reserved capacities attributes as follows:

```
class contractor:

    def __init__(self, tier, region, type, group, activity_years, annual_turnovers):

        self.tier=tier

        self.region=region

        self.type=type

        self.group=group # like qualified for an authority level; e.g MOE and school projects

        self.activity_years=activity_years #provide corresponding years according to the annual_turnovers list; this will be used for future capacity growth rate estimation

        self.annual_turnovers=annual_turnovers
```

Comparator Mechanism team request for information and data structure

the class of contractor includes 6 attributes: (Tiers 1, 2, 3, or 4 should be denoted where annual turnover bands of the Tiers matter and the larger the turnover, the lower the number. Consider Tier 1, >$100m/a; Tier 2, $20-100m/a; Tier 3, $5-20m/a; and Tier 4, <$5m/a. The region can be South island=1, south of north island=2, north of north island=3 or any combinations; e.g. 13. The project type is either horizontal (=1) or vertical (=2) and the contractor's area of expertise is also definable by this classification; it is assumed that each contractor can take only one Sector type (H or V). The group refers to the group of projects that a contractor is an expert in its execution. Project group refers to the project's main function (e.g. school, hospital, road, etc) and it should be set as a string; if no specification exists, then leave it empty. For the activity years attribute, mention the set of years for which the annual turnover is available; e.g. [2012,2015,2019,2020]. Specify annual turnovers with respect to the Tier determined and the activity years; e.g. if the Tier is determined 2, and the set of activity years is [2012,2015,2019,2020], then the annual turnovers should be mentioned as float numbers between 20 and 100 (M$); e.g. [25, 50, 60, 60]).

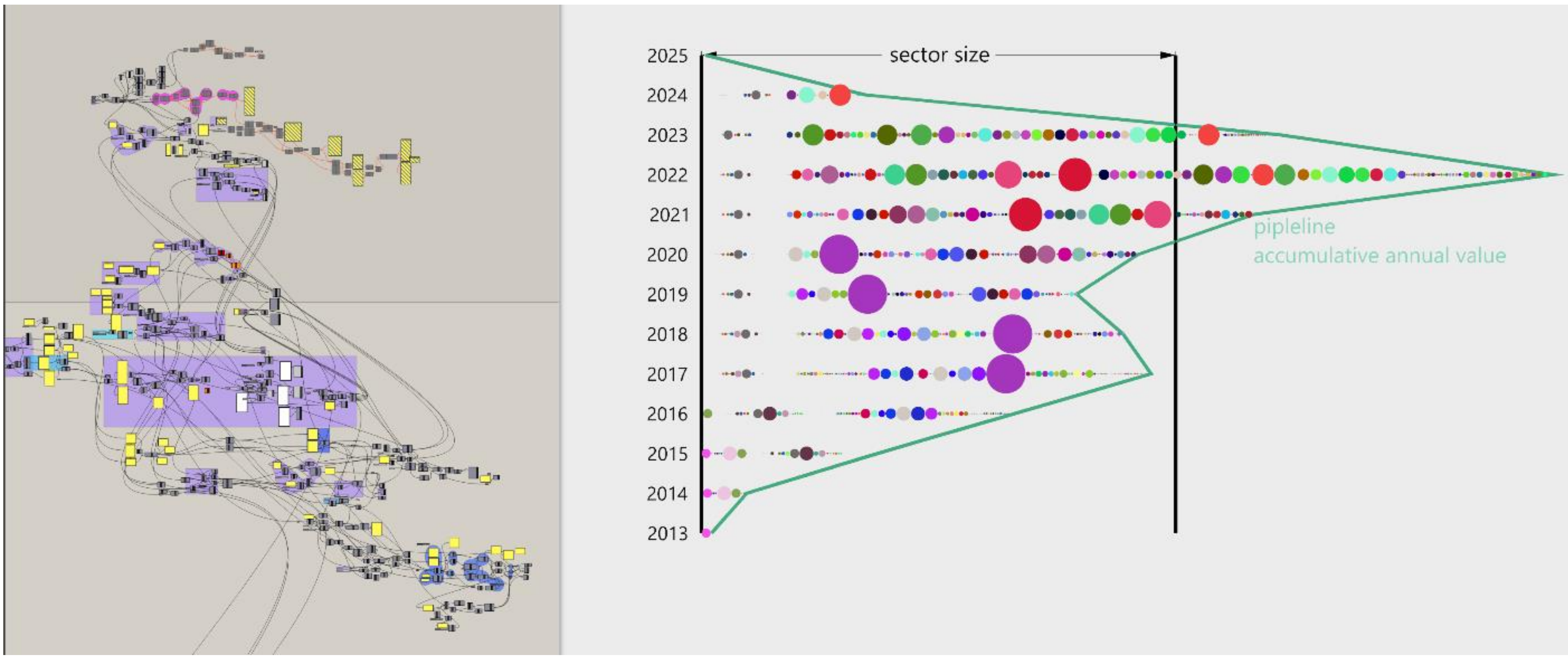
Contractor ID	Tier	Region	Sector Type(H=1,V=2)	Group	Activity years	Annual turnovers	note
0	1	123	2	hospital	2019, 2021	145, 150	The contractors 01 is a tier one contractor and cover the whole 3 regions (1, 2 and 3). It mostly works on vertical sector and hospitals. Its annal turnover for the year 2021 were 150 M$, and for the year 2019 were 145 M$.
1	1	2	1		2016	120	
2	2	23	2		2019, 2020	65,67	
3	2	3	2	residental	2016, 2020, 2021	30, 90,90	

<- Sector|Pipleline->

7 arguments are required to define project attributes: (The "start" and "end" refers to the project's start and end date with the format yyyy or Qn-yyyy. As the last year is excluded from the project duration the "end" year should be rounded up (e.g. if the end date is March 2015, then it should be mentioned as 2016 or Q1-2015). The location of the projects should be defined based on three main regions: South island=1, south of north island=2, and north of north island=3. The project type is either horizontal (=1) or vertical (=2). Also, the project group refers to the project's main function (e.g. school, hospital, road, etc) and should be set as a string. The value attribute considers N million dollars, where N is a positive float number, e.g. 5 M$. Value_distribution is a set of numbers. Each item included in this attribute should be considered as n% for each time step (each year during project execution); e.g. for 5 years of duration, the value distribution set can be [5,25,60,5,5] while the sum of the set items equals 100 and the numbers equal the project's duration years. It also can leave empty to be considered a homogeneous distribution).

Project	Start	End	Region	Type	Group	Value	Value distribution	note
0	2014	2018	2	1	highway	17.5	10,50,20,30	The project 01 starts in the year 2014 and ends in the year 2018 (excluded). It is located in the region 2 and is a horizontal sector project (highway). Its total value equals 17.5m$ where 10% of 17.5m$ is allocated for the first year (2014), 50% of it is allocate for the year 2015, 20% for the year 2016 and the reamin (30%) is allocated for the last year (2017)
1	2023	2025	1	1		5		
2	2016	2022	1	2	hostpital	28.5	50,10,10,10,10,10	
3	2023	2030	3	2	school	26		

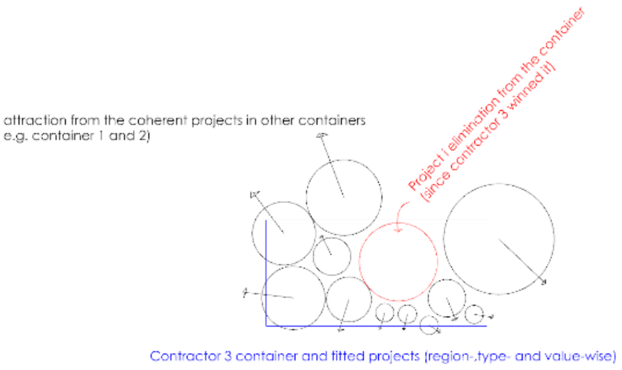
Grasshopper (plugin for Rhinoceros software) canvas; visual programming and data visualization for ABM

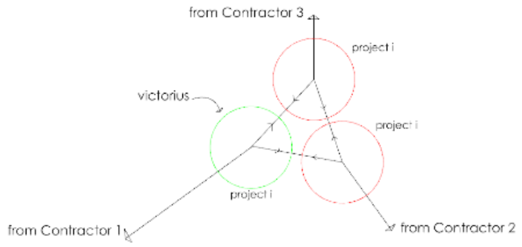


Advanced modelling stages (Considerations)

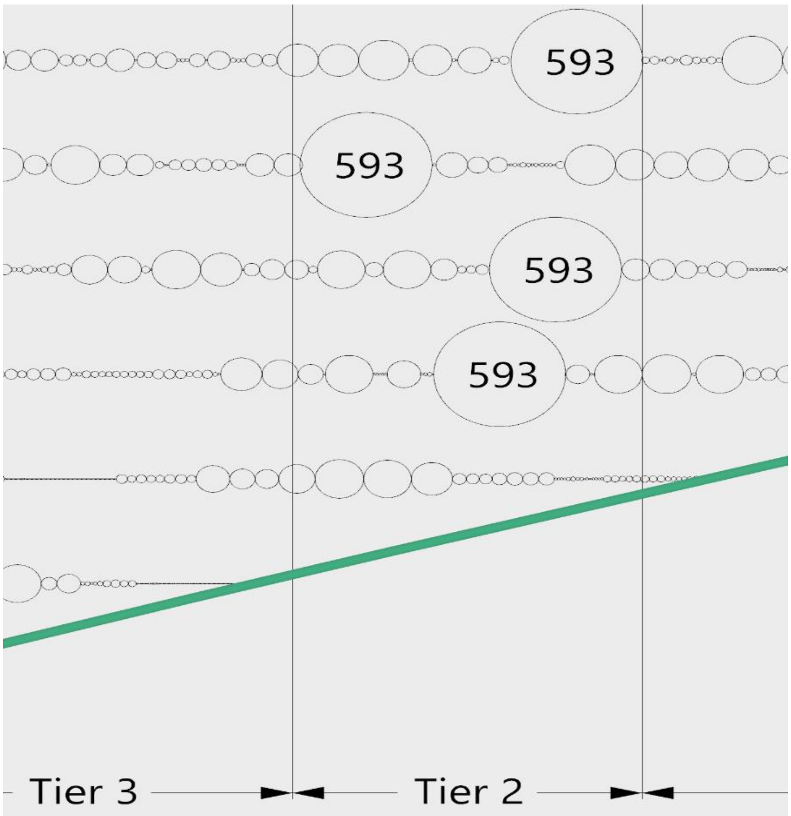
Thus, the main objective of applying ABM is to optimize portfolio settings. The following figure is a graphic narration of what is called contractors' battle (right: environmental forces; left: potential contractor portfolio). The projects i is first temporarily located in contractors 1, 2 and 3 portfolios (based on value, region and type attributes). The contractors then try to attract those suitable projects with a force proportional to:

1) Their entire available capacity
2) Number and value of the projects located in temporary portfolio





The output of the model is again used for plotting the projects within the sector size (divided to contractors' capacities). A potential output is shown in figure below when contractor 2 has taken the project No.593. (in MoE pipeline projects list) The projects are again sorted (left to right) based on starting date but instead of random initial propagation, the result of artificial battle lead the initial locations configurations.



Accordingly, the future research and modeling steps can be taken as follows:

1) Applying subcontracting rules
2) Calculate environmental forces specific to individual agents (based on potential contractors, portfolio loads, and priority levels)
3) Visualize the agents acting in a 2d coordinate system where the sum of environmental forces determines their movements.
4) Extending the model for three main regions and determining regional and typical forces; e.g. how sector size and projects load in NNI effectdynamic contractors capacity in SI or SNI
5) Mapping the graphical model on NZ map, using location data.
6) Comparing sector size and the cumulative projects value
7) Applying optimization techniques to find solutions for touching higher capability levels (e.g. 3d movement for agents and rise their level of intelligence while space exploration)