Title	CAN MULTI OBJECTIVE OPTIMISATION AND GENERATIVE DESIGN TOOLS HELP FACILITATE MORE EFFECTIVE ESTATES DEVELOPMENTS FOR FUTURE SKILLS IN THE TERTIARY EDUCATION SECTOR FOLLOWING THE SFC COHERENCE REVIEW AND THE SCOTTISH GOVERNMENTS INFRASTRUCTURE INVESTMENT PLAN?
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ORCID	https://orcid.org/0000-0002-8417-8855
Type	Thesis
Publication title	
Publisher	
ISSN/ ISBN	
Publication Date	26 January 2024
Version	
DOI	
Repository link	https://ucem.repository.guildhe.ac.uk/id/eprint/103/
Link to publication	

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Abstract

The Scottish Funding Council's Coherence Review of Tertiary Education, published in 2020, reflected on the financial sustainability of the sector where greater collaboration between Colleges and Universities was identified. This coupled with the Scottish College of the Future Report in 2020 identifying similar financial concerns but with that, the opportunity to rationalise regional curriculum offerings to be more meaningful and creating a greater connected educational infrastructure, prompted the author of this architectural thesis to consider the coherence and rationalisation of Educational Estates.

The Scottish Governments Infrastructure Investment Plan 2021/22 to 2025/26 identified needs assessments to predicate the commissioning of new campus buildings with maximising existing assets as well as co locating and repurposing facilities, preferred to the financing of new facilities. Furthermore the Scottish Government current annual spend on the tertiary education sector equates to £3.5bn cut by £33m from the previous financial year, giving a strong indication that capital expenditure for new campus developments will likely be a last resort.

The author identified a Hypothesis that parametric design tools can be used to both collate data on existing facilities assets but also interconnect design objectives that can support needs assessments based on parameters deemed critical to the rationalisation of an exiting estate. The hypothesis worked on the principle of upscaling the parametric design tools in order to prepare a federated ecosystem of buildings, whereby asset utilisation in inter-regional facilities could potentially be aligned with regional skills needs, thus aligning with CSIC's Future Skills Strategy, where centres of excellence and skills academy models are being proposed.

Using visual programming via the Grasshopper plug in for Rhino, data sheets for Fife Colleges new Dunfermline Learning Campus allowed a generative model from Excel data to be created, giving a conceptual mass which was then bin packed to another Grasshopper component named Wallacei. This was to generate design permutations using pre-defined fitness objectives. Whilst the end results did not have the anticipated impact identified in the hypothesis, what was identified was the need for more user-friendly interfaces and beginning with the refinement of single fitness objectives prior to embarking on more ambitious multi objective optimisation workflows.

Multi objective design tools can however, offer huge potential for the tertiary education sector to align physical estates with policy and curriculum planning tools to determine optimisation of regional facilities as well as supporting future needs assessments that are critical if investment for future infrastructure investments is sought from the Scottish Government. The ability to do so requires collaboration from stakeholders between centres. The East Central Scotland Colleges Collaboration provides that particular consortium of colleges the opportunity to begin this process through supplying an audit of one another's estates infrastructure into a coherent data set to begin establishing workflows for both generative and multi objective optimisation design tools that can help plan for future needs assessments in a coherent manner, driving optimised estates utilisation for a sector and reducing unnecessary capital expenditure.

1.0 Introduction

The future provision of Tertiary Education is undergoing a significant debate both in a Scottish and UK context. In particular, the Scottish Funding Council are currently undertaking a Coherence review of College and University provision with a view to reforming the provision of Tertiary Education, both in the immediate post COVID emergency years from 2020-22 to more medium to longer term horizons. Similarly, a UK Independent Commission has produced a College of The Future report aimed at answering two simple questions: what do we need from colleges from 2030 onwards and how do we get there?
Whilst these publications give the stimulus for debate and discussion about the provision of Tertiary Education in the future, there remains many questions that perhaps deserve more detailed scope in terms of the implication of the findings, out with, but not excluding discussion points such as pedagogical and collaborative ideologies.

To compliment the many Education sector specific publications that will be reviewed in this dissertation, it would be naïve to not hypothesise the implications of Industry specific literature to shape a College of the Future in terms of both the educational provision of and estates configuration to meet the needs of industry.

Whilst providers of Tertiary education can facilitate a range of skills sectors, this dissertation will focus on the Architectural, Engineering and Construction (AEC) sectors, drawing reference to literature such as the 2016 Farmer Review where a dysfunctional training funding and delivery model was identified. This coupled with opportunities for automation and digitisation of the industry will help provide a frame of reference where the educational infrastructure required to meet the pedagogical and technological advancement is discussed and considered for planning a physical estate or building to facilitate the learning of knowledge and skills.

The creation of educational estates that are fit for purpose for the future is a challenge. Tertiary education typically takes place in schools, colleges and universities, meaning capital expenditure for physical infrastructure and resources is divided across all three sectors, giving rise to resource and infrastructure duplication. Coherence is a challenge but does this give rise to an opportunity to federate the allocation of government capital expenditure to eliminate waste, ensuring that funds are allocated proportionally to the specialised locations of skills training, thus creating centres of excellence that are appropriately resourced and can be versatile to adapt to rapid change?

From a design perspective, this is an enormous challenge. New facilities will require to be designed on the basis of resources and infrastructure that is already in place within a region / country, meaning localised projects may inevitably be scaled down owing to the presence of existing, underutilised facilities in the region or out with. If we consider the educational infrastructure of Scotland, with 15 Universities, 26 Colleges and 358 High Schools, to federate the existing estates and infrastructure for each of these would be an astronomical task using conventional methods. However, if this was to be done, it would set the scene for informed design, meaning capital expenditure can be allocated on the aforementioned basis, ensuring resource optimisation in the country. The glue that binds all of this together is Big Data. Federating this in digital design is not impossible but the requirements of collation and analysing is one that can make use of static data and turn this into a live tool when considering both the design and allocation of expenditure to educational estate developments. Essentially, digitally twinning the educational estate network, albeit, by using parameters that are only critical to allocation of resource.

In order to do this, it is important to first consider the requirements of an individual institution and the parameters critical to ensuring the campus itself is designed and utilised appropriately . To do this, a case study of the new proposed Fife College Dunfermline Learning Campus will be used and multiparameter optimisation design tools will be used to generate a model that represents that particular campus. Doing this will allow opportunities to test the scope of parameters that will be crucial to upscaling the potential of a federated concept for the whole of Scotland.

This dissertation will begin by reviewing literature that is critical to the coherence of educational estates as well as their fitness for purpose in meeting the current and future demands of the AEC industry, including pedagogical change in service design and delivery for institutions. Accompanying this will be literature of multi parameter optimisation / digital design tools and their use for both design and federation of models based on specific user inputs.

Following the literature review, the digital design tasks will begin with analysis and commentary throughout before culminating with evaluations and conclusions. The initial objectives for the thesis are as follows:

- Identify what physical infrastructure opportunities exist for current skills and training providers in response to the Coherence report and Recovery Plan.
- Alignment of adjacencies and affinities of technical facilities to encourage interdisciplinary and interorganisational collaboration.
- Demonstrate how static data can be converted into a generative building programme.
- Create a building programme / definition for a future skills provider to configure estates arrangement that can be part of a scalable digital estates eco-system.

2.0 Literature Review

2.1 The Scottish College of the Future: The Independent Commission on the College of the Future

In October 2020 The Scottish College of the Future report was published, drawing reference to a Scotland specific version of an Independent UK Commission's College of the Future with the aim of ascertaining what is required of colleges from 2030 onwards, and what is required from colleges to get to that point.

The commission proposed 10 recommendations:

- [1]*Creating an integrated and connected tertiary system*
- *Building on regionalisation*
- *A coordinated approach outcome agreements*
- *A balanced and streamlined approach to funding*
- *Amplifying the role of colleges as a strategic support to employers across innovation and skills*
- *Deepening strategic alignment*
- *A systems-wide approach to procurement*
- *Colleges leading the way in digital transformation*
- *Qualifications for the Future Workforce*
- *Leading the way: an ambitious workforce strategy, with diverse and representative systems leaders*

The main themes emanating from the review rely upon collaboration and alignment with more strategic partnerships between colleges, universities and industry to ensure a fit for purpose tertiary education system which delivers high quality outcomes that contribute to Scotland's economic and social prosperity.

Educationally, the report also recognises the impact of closer collaboration between schools and colleges for post Nat 5 and post-14 qualifications, meaning coherence is every bit as important by means of what courses and skills are being delivered as well as the estates and physical infrastructure required to deliver.

[1] The Independent Commission on the College of the Future. 'The Scottish College of the Future: A Nations Specific Final Report', 2020. https://www.collegecommission.co.uk/the-scottish-college-of-the-future.

Recommendation 5 of the report *Amplifying the role of colleges as a strategic support to employers across innovation and skills* suggests that [2]*a national network of specialist "Hubs" be established to address critical skills shortages, especially in relation to higher level technical skills (e.g. STEM/digital) and acting as a focal point for employer partnerships as well as extending access to learning opportunities in areas of population sparsity.*

To contextualise what this means for the AEC sector and drawing reference to the Construction Scotland Innovation Centre (CSIC) which in itself is regarded as a specialist hub, academic partners and industry can gain access to cutting edge, specialist facilities to not only enhance collaboration but create a centre of excellence. CSIC themselves indicate in their Future Skills Strategy that key skills and behaviours are digital advancement, culture change as well as green credentials, meaning that the industrialisation of construction may not necessitate every centre requiring space and provision of specialist equipment to support this, begging the question about the future need for large "factory floor" type spaces at every institution.

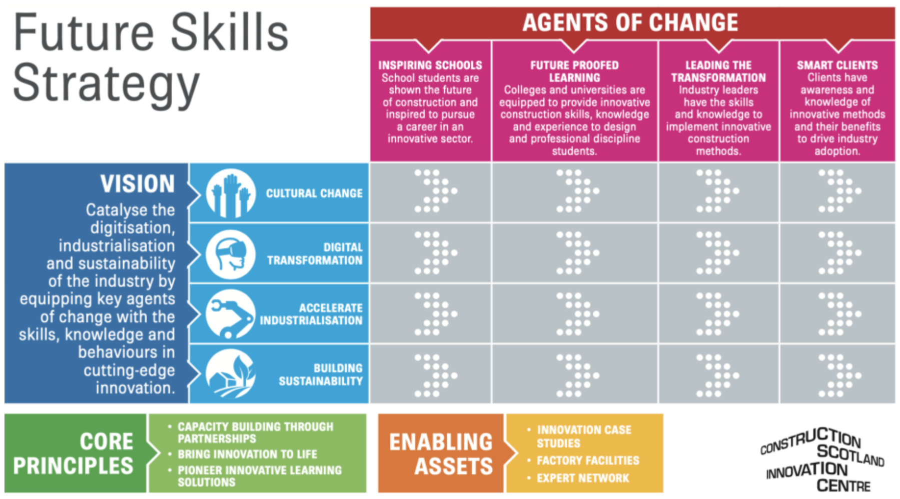

Figure 01: CSIC Future Skills Strategy

The coherence of these facilities across Scotland will lead to less capital expenditure on repeat assets but also encourage greater collaboration between industry and academia. In the provision of future estates, the infrastructure must be versatile to acknowledge the transitional arrangements as well as requirements of "semi-specialist" facilities to support the short to medium term mainstream educational need of learners. Whilst digital advancement for construction is a desirable target, without mandatory or regulatory requirements for businesses to do so, the sector demand will still require traditional construction crafts in specialist, high volume workshop spaces. Whilst statutory regulations may change over time, the transitional arrangements for the short to medium term will require suitable spaces for this provision.

2.2 Coherence and Sustainability: A review of Scotland's Colleges and Universities Phase One Report: Insights to Develop Further

The phase one Coherence and Sustainability review of Tertiary Education in Scotland was conceptualised to provide all stakeholders in Post 16 education, with a reflection of both the financial sustainability of the sector but also what the future may look like in the Scottish Education system by providing a range of options for stakeholders to consider when determining its future.

Figure 02: Objectives of the Coherence and Sustainability Review of Scotland's Colleges and Universities

Contributors to the review which included colleges, universities and SFC board members agreed on ten broad ranging themes:

- Keeping the interests of current and future students, and equalities, at the heart of everything we do.
- Supporting the digital revolution for learners.
- Towards an integrated, connected tertiary education and skills eco-system for learners and employers.
- Recognising colleges and universities as national assets and civic anchors.
- Building long-term relationships with employers and industry.
- Protecting and leveraging the excellence of our research and science base.

[2] The Independent Commission on the College of the Future. 'The Scottish College of the Future: A Nations Specific Final Report', 2020. https://www.collegecommission.co.uk/the-scottish-college-of-the-future.

- Driving the innovation agenda.
- Enhancing collaboration.
- Making the most of the sector's global connections.
- Financial sustainability and funding.

Evidently from the themes identified, there is opportunity for estates and educational provision to be considered more integrated and collaborative with a strong emphasis on an employer/industry focus. Specifically looking at theme three: **Towards an integrated, connected tertiary education and skills eco-system for learners and employers.** *many see the ability to plan collaboratively across all relevant partners at a regional level as key not only to the learner journey, but to the delivery of skills and training that unlock our capabilities around decarbonising our economic recovery and leveraging our natural capital, to the way we develop clusters around Scotland that maximise our investment in world leading strengths such as digital and data, precision medicine, quantum, life sciences, and advanced manufacturing.*

What this insinuates is that there is an opportunity to rationalise curriculum offerings in place of more specialised delivery centres that are providing service in a more coherent manner such as college partnerships with both universities and industry. This would allow government to invest significantly in specialist areas to be world leading facilities rather than funding a series of lesser standard facilities across the nation. The Scottish Funding Council currently spends £443M in Grant in Aid funding for the college sector for its Learning and Teaching which is 89% of its total spend for the college sector.

UPRATED PRICES	Credit target 2020-21	£237 PG1	£269 PG2	£314 PG3	£403 PG4	£417 PG5	Gross price per credit	Tuition fees from outside SFC (per credit)	SFC price per credit	SFC credit funding
		Subject Mix								
Ayrshire	124,877	18%	44%	35%	1%	3%	£285	£30	£255	£31,824,637
Borders	25,630	6%	45%	36%	7%	6%	£301	£26	£276	£7,065,689
Dumfries and Galloway	30,798	11%	48%	36%	0%	5%	£289	£31	£258	£7,955,821
Dundee and Angus	107,405	20%	41%	29%	3%	7%	£290	£29	£261	£28,044,608
Edinburgh and Lothians	187,869	18%	52%	25%	0%	5%	£282	£36	£246	£46,260,302
Fife	132,489	19%	44%	30%	0%	6%	£286	£34	£252	£33,382,066
Forth Valley	85,887	14%	42%	37%	0%	7%	£291	£38	£253	£21,700,821
Glasgow	384,975	17%	47%	26%	1%	9%	£289	£44	£246	£94,613,166
Highlands and Islands	112,382	14%	37%	40%	5%	5%	£296	£18	£278	£31,279,747
Lanarkshire	181,644	14%	42%	38%	0%	6%	£290	£35	£255	£46,356,377
Newbattle College	921	85%	0%	0%	15%	0%	-	-	-	£917,345
North East Scotland	132,005	16%	52%	29%	0%	4%	£283	£35	£248	£32,724,615
Sabhal Mor Ostaig	799	0%	100%	0%	0%	0%	-	-	-	£1,756,537
SRUC	22,747	1%	23%	4%	66%	6%	£368	£18	£351	£7,979,592
West	158,693	16%	45%	27%	0%	12%	£293	£38	£255	£40,436,790
West Lothian	44,353	17%	57%	24%	0%	2%	£278	£35	£243	£10,762,806
	1,733,472	**16%**	**45%**	**30%**	**2%**	**7%**	**£289**	**£35**	**£254**	**£443,060,919**

Figure 03: Scottish Funding Council Funding Allocation per College

Overall Scottish Government planned budget expenditure across the tertiary education sector as a whole for 19/20 amounts to almost £2bn of which £30m can be attributed to depreciation costs of infrastructure and estates. Whilst this is a small portion of the budget, it can also be assumed that ageing facilities will have exceptionally higher running costs leading to estates being huge liabilities to the government and counterproductive in Scotland's aspirations in the desire to become carbon neutral by 2045.

[3]*The university estate is significantly larger than the college estate. Approximately 25% of the university estate is in poor condition and the sector has reported a current backlog need of up to £900m. SFC continues to provide capital maintenance funding which, in turn, allows institutions to lever in significantly more investment from other sources. The Scottish Government will also provide Scottish universities with access to up to £60m in Financial Transactions in 2019-20. This builds on Financial Transactions provided in previous years and will be targeted at supporting further university campus development to improve the learner experience and reduce the sector's carbon footprint.*

An aspiration of the Scottish Government is internationalisation of the country's economy, particularly pertinent in a post-brexit economy. Education is an economic asset however, with the correct digital infrastructure in place, hosted in Scotland, Scottish Colleges and Universities can offer services across the globe which would perhaps modernise the approach from the one that Strathclyde University took in 2014 with their New York City Campus at a cost of £11.5m which by 2017, still did not have degree awarding status in the USA resulting in further wasted capital expenditure and reputational damage.

Fig04 presents a reduction in capital expenditure of 39% for the college sector and 15% for the university sector equating to an overall reduction of £33m from the previous year which in itself leads to question about the Scottish Governments commitment to increase capital for investments in ageing estates and infrastructure as well as financing new facilities.

[3] Scottish Government. 'Scotlands Learning Estate Strategy', n.d. https://www.gov.scot/publications/scotlands-learning-estate-strategy-connecting-people-places-learning/pages/11/.

Level 2	2017-18 Budget £m	2018-19 Budget £m	2019-20 Budget £m
Learning	217.0	237.7	257.8
Children and Families	167.2	151.5	123.9
Early Learning and Childcare Programme	–	–	40.5
Advanced Learning and Science	6.2	6.2	10.0
Scottish Funding Council	1,734.8	1,838.0	1,839.3
HESS	940.0	946.4	922.5
Skills and Training	223.7	232.8	254.0
Total Education and Skills	**3,288.9**	**3,412.6**	**3,448.0**
of which:			
Total Fiscal Resource	2,462.2	2,577.8	2,657.1
*of which Operating Costs**	–	–	*37.3*
Non-cash	212.3	235.8	243.4
Capital	157.4	131.0	94.5
Financial Transactions	14.0	40.0	55.5
UK Funded AME	443.0	428.0	397.5

Figure 04: Scottish Government Spending Plans 2019-20 Budget https://www.gov.scot/publications/scottish-budget-2019-20/pages/10/#Tab8.01

Whilst the Coherence and Sustainability review has a focus on shorter to medium term objectives, Colleges and universities are already making rapid adjustments to respond to post COVID-19 demands and ways of delivering service. [4]*More profound changes that affect students, curriculum delivery, financial and business models, or physical estates in different states of adaptability will need longer term transition and adaptation.*

It is clear the immediate post COVID-19 challenges will require prioritisation but securing the long-term financial sustainability of the sector is clearly reliant upon more coherence between all stakeholders. The rationalisation of regional FE and HE estates could be regarded as an opportunity to make more effective rationalisation of building infrastructure, thus reducing annual capital spend but also making more effective utilisation of campus buildings both regionally and across the country. To do so, a significant estates and resource inventory audit for all Scottish Colleges and Universities would have to be generated to paint a true picture of resource availability and its utilisation. Land acquisition costs alone for new buildings can be a significant cost from capital expenditure, thus coherence and utilisation of facilities should reduce this in future.

On the latter point skills and training models are not exclusive nor the sole responsibility of Colleges and Universities. As is common in the oil and gas sector, many employers host their own exclusive training centres with sector leading facilities. One such example in the construction sector is Forster Roofing based in Brechin, Angus who have invested in a 4 year project to create their own specialised roofing training centre with the aim of training 24 apprentices over 4 years. Given current delivery models for 4 year apprenticeships, and if we take Fife College's current workshop space for roofing apprentices as a precedence, which measures 200m2, that is a significant space for 24 workplace apprentices who would be using the facility on block release meaning full utilisation would not necessarily be achieved, especially if we consider skills and training centres as community hubs with potential to be open at evenings and weekends. This creates further rationale to collate raw data on asset utilisation and resources in both private and public sector facilities for the common good.

2.3 The Scotland Infrastructure Investment Plan 2021-22 to 2025-26

The Scotland Infrastructure Investment Plan 2021-22 to 2025-26 helps provide a framework for government investment in its estates and infrastructure, setting out a clear vision for future infrastructure which supports an inclusive net zero emissions economy. [5]*Underpinning this vision are three themes: enabling net zero emissions and environmental sustainability; driving inclusive economic growth; and building resilient and sustainable places. These also complement the Missions of the Scottish National Investment Bank.*

To assist the planning and decision making process, the Investment plan recommends an investment hierarchy framework be created with the aim of enhancing and maintaining assets over new build to both protect the environment and ensure value for money.

[4] Scottish Funding Council. 'Coherence and Sustainability: A Review of Scotland's Colleges and Universities Phase One Report: Insights to Develop Further', n.d. http://www.sfc.ac.uk/web/FILES/corporatepublications_sfccp052020/Review_of_Coherent_Provision_and_Sustainability_Phaae_1_Report.pdf.

[5] Scottish Government. 'A NATIONAL MISSION WITH LOCAL IMPACT: Infrastructure Investment Plan for Scotland 2021-22 to 2025-26', 2021. https://www.gov.scot/publications/national-mission-local-impact-infrastructure-investment-plan-scotland-2021-22-2025-26/.

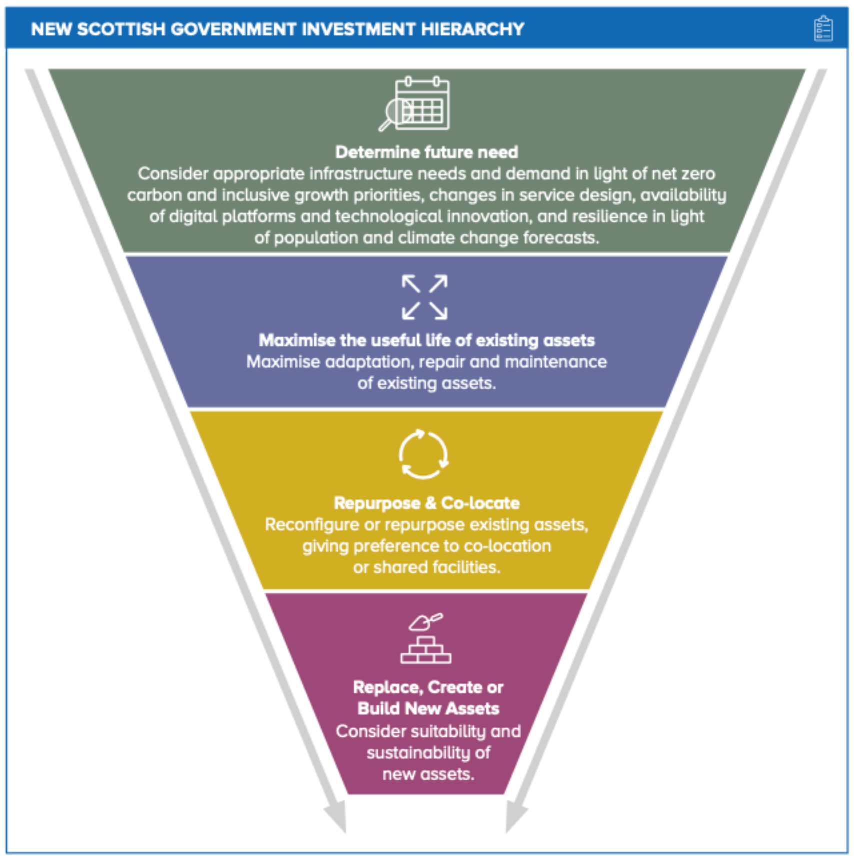

Figure 05: New Scottish Government Investment Hierarchy: Infrastructure Investment Plan for Scotland 2021-22 to 2025-26

The investment hierarchy will encourage each step indicated in Figure XX to be considered before confirming the correct approach for a project. Examples could include where there is a service need for a facility or if an existing asset can not be repurposed. In this Investment plan, the Scottish Government also indicate that higher proportions of investment will be directed to the initial stages of the hierarchy, and are committed to doubling investment in maintenance and asset enhancement over the next five years.

The investment hierarchy is a welcome strategy, particularly given the coherence of tertiary education. Determining future need is extremely important in terms of planning, currently no federated estates eco system exists, meaning local decisions/compromises may have to be made in order to realise the true potential of resource sharing. Disposal strategies by local authority's, educational establishment and industry can often be a process conducted in isolation without due regard for the consideration that an estates liability to one party could be a desirable asset for another, which could attract more funding for regeneration than what would be available for a new build in line with the investment hierarchy.

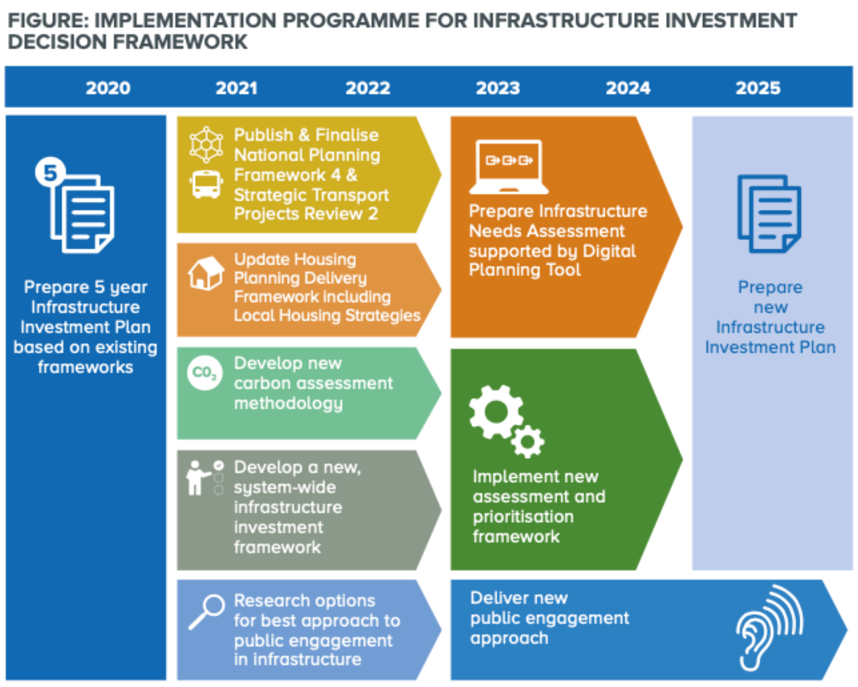

Figure 06: Implementation Programme for Infrastructure Investment Framework

2.4 Infrastructure Data Gathering Precedents: Civtech / Midlothain Council / Scottish Futures Trust

Part of the implementation programme for the infrastructure investment decision framework requires a Digital Planning Tool to support infrastructure needs assessments. In an interview with Paul Dodd, Senior Associate Director for the Infrastructure Technology Workstream for the Scottish Futures Trust, it was reported that a Civtech challenge project is currently underway with Midlothian council with the aim of better understanding how a classroom, or school is utilised, with the aim of deriving the following benefits:

- [6]*Support pupil wellbeing through enhanced user experience.*
- *Identify new capacity within our buildings for growth and expansion.*

[6] Civtech Alliance. 'Challenge 7: How Can Tech Help Us Understand How Our School Buildings Are Used, and Help Support Asset Performance, Wellbeing and Sustainability?', n.d. https://www.civtechalliance.org/civtech-6-challenge-7-school-building-use.

- *Improve the learning environment through data driven building management decisions. Where we know patterns of high utilisation, preventative measures can be taken in improving the environmental conditions of that space to reduce CO2 levels, reduce heating levels earlier in response to high utilisation and create improved learning environments.*

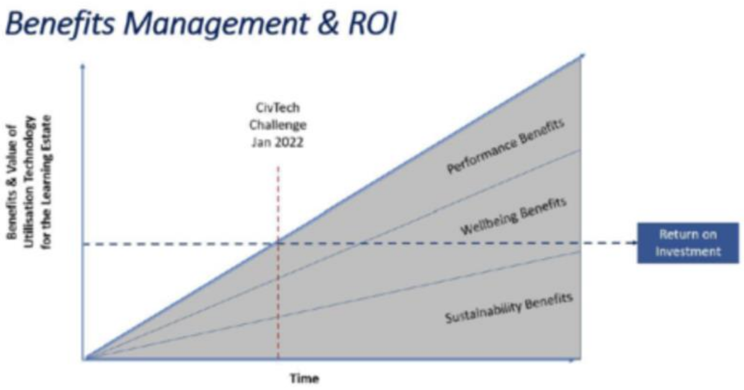

Figure 07: Developing Benefits Case and ROI for Challenge Solution for CivTecg/SFT/ Midlothian Council Project

Whilst this process is heavily reliant upon sensor technologies and live asset performance with IoT etc, it demonstrates that not only can the space and estate utilisation be audited but data gathering which is relevant to adapt the configuration of the learning environment to inform the creation of conditions more conducive to learning will improve the wellbeing of building users all whilst potentially offsetting CO2 emissions through creation of sustainability heat maps generated by better utilisation of data.

Whilst the opportunity to enhance existing assets is one that will require a range of retrospective data collation and federation, it is the creation of new buildings give tremendous opportunity to begin the data collation and federation at design stage whereby designers, building users and government stakeholders can make use of data for both building legacy and operation matters but also to support design decision making based on predefined parameters such as adjacencies, CO2 targets and design permutations for optimisation.

2.5 Infrastructure Data Gathering Precedents: Bryden Wood / PriSM / Cast Consultancy / Mayor of London

Design Automation is a concept often associated with standardisation and bog standard, repetitive typology design. Whilst the perceived removal of the architectural freedom and flair associated with vibrant design aesthetics may be negatively perceived by traditionalists, Bryden Wood, a company specialising in creative technology use in AEC industries have developed an open source platform called PRiSM App which on a domestic front, [7]*brings together central and regional government, funders, developers and manufacturers and drive a step change in productivity and quality in homebuilding.*

Figure 08: Example from PRiSM App: www.brydenwood.co.uk

The PRiSM app is certainly a welcome tool for to assist design decision making processes through its presence of MMC design concepts, planning parameters and local amenities / transportation infrastructure as well as geographic feature. Perhaps at this stage in its development it is of greater assistance as a planning tool to support a data rich planning process but certainly one that can bring many efficiencies to what can often be a disconnected process. However, this concept is one that a connected eco system for an FE/HE estates configuration, can mirror some of the efficiencies gained through the planning and early design process.

To assist this, the standardisation of estates buildings to an extent would have to resemble DfMA concepts in order for standardised approaches to be considered and give greater design and cost certainty . A standardised approach to a normal classroom and its configuration is one that can hypothetically be replicated from estate to estate, begging the question as to why can't classrooms be standardised across a connected eco-system for future new buildings? This would be a more difficult assumption to make across an ageing estate but for future new build planning, the ability to transform the design process by creating an integrated design system, given the scale of government funded educational estates would add significant value through adopting a programme wide approach rather than treating each new build as an unrelated, individual project.

[8]*In a traditional, one off project, each asset is modelled and information for design, tender and construction created individually. The design team can only afford to describe the proposed solution to a certain level of detail, which is then developed by the contractor in conjunction with their supply chain. Typically the degree of repetition at project level is low and only warrants highly detailed analysis of a few key areas.*
The fact that the design development (project knowledge) often takes place in isolation from the supply chain is a significant source of missed opportunities to optimise the design and leverage best in class construction knowledge.

[7] Bryden Wood. 'PRiSM App', n.d. https://www.brydenwood.co.uk/projects/prism-app/s92421/.

[8] 'Delivery Platforms for Government Assets: Creating a Marketplace for Manufactured Spaces'. © Bryden Wood Technology Limited, 2017.

In addition, most of the construction knowledge sits within the supply chain which may be fragmented and have little opportunity to collaborate. This is a significant source of rework and duplication of effort.
As a result, any benefits that are generated by innovation generally remain within the supply chain and are not passed on to the client for wider use. Any knowledge that is gained through the project cannot typically be captured, disseminated and improved upon to the benefit of other projects.
Considerable value can be therefore be generated through creation of a suite of standardised solutions and repeatable elements that are simply configured differently for different sites and project requirements.

Developing components for a large scale deployment, where knowledge is captured and retained for further collaborative refinement, would facilitate continual improvement (as is common in the automotive and aerospace industries) as opposed to constant reinvention (as is common in traditional construction).

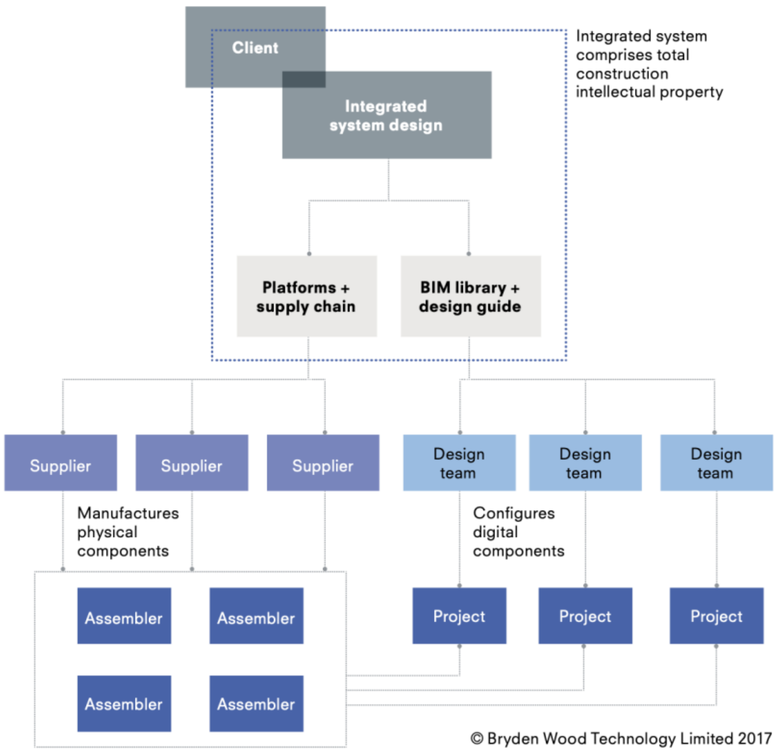

Figure 09: Integrated System Demonstrating Construction Knowledge and IP

Whilst the benefits of a long term, data informed automated design process would allow all stakeholders to be heavily involved in major design decisions at most stages of a project, it is an aspiration that requires a tremendous amount of data collation but most importantly the continuous culture shift in mindset about how FE/HE estate contracts are procured, designed and built. This is evolutionary and as yet, no project on the scale of the design of a new campus building has been designed in this manner. For Scotland, this would require a pilot project to undertake this exercise, fundamentally first to collate data before any design computation takes place. This would be a labour-intensive task to get to this point but it is one that is necessary and would over time lead to greater effectiveness in a digital DfMA process.

The amount of parameters required for a FE/HE estates project would be very broad ranging and could over complicate a proof of concept. For a refined project and new methodology that could be adopted in the future, reference to COBie data drops at relevant stages in a project would prevent this methodology becoming too data rich too soon. To develop a proof of concept, simple parameters should be considered with the view to demonstrating scalability.

2.6 Optimising Spatial Adjacencies Using Evolutionary Parametric Tools: Using Grasshopper and Galapagos to Analyse, Visualize, and Improve Complex Architectural Programming

Perkins + Will's Research Journal 7.02 presented the use of the Grasshopper and Galapagos plug ins for Rhino to a precedence in terms of how parametric design and analytical tools can be used to represent and optimise adjacency requirements, offering alternative analysis of how complex adjacencies can be programmed via interconnected programmatic elements.

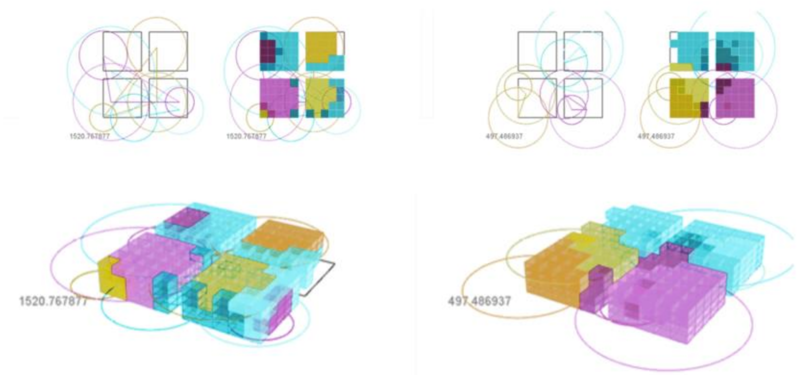

Figure 6: Least fit result (left) and most fit result (right).

Figure 10: Space Planning Optimisation Example from Perkins + Will Journal

[9]*Academics and practicing architects realized that the implications for parametric design are larger than generating unusual forms. In the past two decades, parametric tools have been used to enhance the design process, allowing architects to iterate more quickly and focus on optimizing the performance of a building. These optimizations have focused on topics as varied as reducing energy use, improving the flow of passengers in an airport, and space layout planning.*

The hypothesis that parametric tools can be used to support defined parameters that are critical to achieving a successful building based on client / user requirements requires further exploration. As Boon et al emphasised *This type of approach offers a unique system of analysis that can create an extensive range of unique and otherwise unexplored solutions when faced with problems in developing complex order for spatial relationships.* In essence, when considering the design of a mutli-campus, multi-organisational infrastructure, can evolutionary solvers be used to not only programme spatial adjacencies in one building but also federate a series of facilities in more than one geographic location to optimise the what facilities are required and where?

3.0 Methodology

Following the literature review, the rationalisation and coherence of FE/HE estates is an opportunity to demonstrate the capabilities of parametric design tools, in particular multi-parameter optimisation to support automation of design decisions and bring an opportunity to further develop the collation of big data towards digitally connected tertiary estates.

What is clear is that silo's of data exist for this infrastructure, typically held by estates teams at each institution with designer / facilities input at relevant stages ranging from conceptual design of new buildings to existing facilities.

In the absence of an eco system where such data is federated, the intentions of this thesis is to demonstrate how this data can be collated and the intentions are to use research methods to unpick the opportunities that exist but also the challenges faced not only in the federation of data but also the placement of parameters critical to an individual institutions operational need but the wider, regional and national parameters with coherence of curriculum and estates resource.

The research methods adopted in the literature review allow a critical analysis of the various articles and literature to inform an opinion of the opportunity that exists to use parametric design tools within the FE/HE sector to support the rationalisation of estates as part of the long term coherent vision of the tertiary education sector.

3.1 Parametric Design Methodology

The parametric design will comprise of two phases to fulfil the opportunities identified in the literature review. Phase 1 will focus on the generative design of a new facility using raw data that can be programmed to generate a design whereas Phase 2 will concentrate on using multi-parameter or objective optimisation methods to modify the concept facility where optimised design permutations are presented and assessed. An aspiration of this thesis is to create a sister building where alignment of physical infrastructure can create coherent estates in two setting centres with their collective operational and strategic needs federated through multiparameter optimisation. These phases will be presented as Chapter 1 and Chapter 2 with findings for each phase recorded at the end of each chapter.

3.2 Chapter 1: Parametric Design Phase 1

Given the nature of the building in respect of a Tertiary Education centre which typically has complex spatial relationships and high adjacencies, this leads to a high number of programmable elements, meaning like a typical design process, data collation and programming will naturally have to precede any design related activity. In the context of design computation, [10]*during conceptual and schematic design stages, much of what is explored involves theoretical concepts. The work is expressed diagrammatically. If the concept can be distilled into numerical parameters, then it is possible to use parametric modelling. This type of analysis allows designers to explore a much wider range of options in a much shorter timeframe.*

The platforms used for this particular exercise are Rhino 3D and Grasshopper with various plug-ins that will be expanded upon later, to support definitions used to generate the design process. As alluded to in the introduction, Fife College have kindly supplied data sheets pertaining to their new proposed Dunfermline Learning Campus (DLC).

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[9] Christopher Boon, Portland State University, Corey Griffin, Assoc. AIA, Portland State University, Nicholas Papaefthimious, AIA, LEED AP BD+C, ZGF Architects LLP, Jonah Ross, ZGF Architects LLP, and Kip Storey, ZGF Architects LLP,. 'OPTIMIZING SPATIAL ADJACENCIES USING EVOLUTIONARY PARAMETRIC TOOLS: Using Grasshopper and Galapagos to Analyze, Visualize, and Improve Complex Architectural Programming'. *Perkins & Will Research Journal* 7.02 (n.d.).

[10] Christopher Boon, Portland State University, Corey Griffin, Assoc. AIA, Portland State University, Nicholas Papaefthimious, AIA, LEED AP BD+C, ZGF Architects LLP, Jonah Ross, ZGF Architects LLP, and Kip Storey, ZGF Architects LLP,. 'OPTIMIZING SPATIAL ADJACENCIES USING EVOLUTIONARY PARAMETRIC TOOLS: Using Grasshopper and Galapagos to Analyze, Visualize, and Improve Complex Architectural Programming'. *Perkins & Will Research Journal* 7.02 (n.d.).

Figure 11: Fife College's Proposed Dunfermline Learning Campus

Contained within the data sheets (appendix folder 1) is raw information relating to room volumes, adjacencies as well as specialised room assets / requirements such as plant, lighting / mechanical requirements. The intentions are to use samples of this data to demonstrate a proof of concept that a design can be automated through programming adjacencies and affinities prior to design optimisation being considered.

The volume of data available is welcome but a data rich solution could cause too much conflict with extraction of relevant data necessary for the generation of design adjacency programming and inevitably would require further development of python scripting to have a fully automated solution that solved too much, too soon in the early stages of design development.

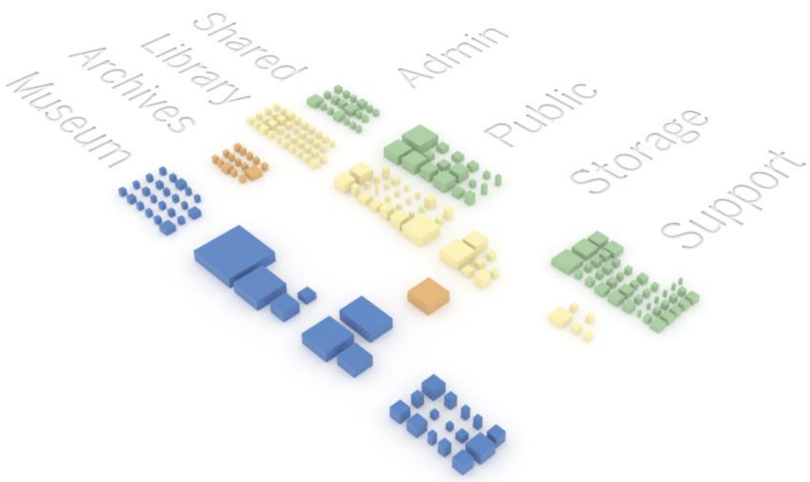

Figure 12: Example of LMNTS HUD Showing Programmable Spaces for a Public Facility

All rooms will be identified through room numbers and an allocated colour to support the creation of a heads up display (HUD) for all stakeholders to view the design in Realtime. Many other parameters could be considered such as establishing site specific information but this will be presented generically further in this thesis and as previously mentioned, could present too much stagnate, unnecessary data for the purposes of this thesis.

Prior to establishing a workflow for using digital design tools to create the building mass, it is important to plan a diagram to establish process and information required to culminate in the creation of a conceptual mass.

Determine Building Data
Collate Data Sheets for DLC
Programme Room Areas
*Programme Adjacencies (Possibly in Phase 2)

Input Parameters
Determine Constrained Area (Site)
Programme Parametric Definition
Determine Obstacles
*Programme Adjacencies (possibly in Phase 2)

Using Excel as a means to collating data and transforming this from the DLC data sheets, this will then be presented in a format where data can be segregated into categories:

- Room Names
- Room Area (length and breadth)
- Ceiling Height
- Room adjacencies (using adjacency matrix)

Initially the spaces will be computed as volumes using Grasshopper plug ins within Rhino before considering programming adjacencies through the creation adjacency matrix.

What is important to clarify is that using the associated tools within Grasshopper for Rhino 3D may require trial and error as well as enhancement of definitions which may require elements of debugging and upgrades. Such is the fast-moving pace of open source visual programming tools within Grasshopper, it would be prudent to look at precedents of definitions that may help support the initial phase of building programming and the associated assembly of the room volumes.

The intended software to complete Phase 1 is Grasshopper within Rhino 3D but using PackRat to box the Geometry created from the data articulated by the Excel Reader from the DLC data sheets. Full definitions and programmes will be presented in the results/analysis section.

3.3 Chapter 1: Parametric Design Phase 1 Results

Within Grasshopper, the ability to read data from Excel spreadsheets to convert into geometry in Rhino 3D removes the requirement to manually generate using conventional CAD design tools within the software engine which could lead to efficiencies in the design process through automated generation of volumes.

In order to do this, designing a grasshopper definition that can read data and convert into identifiable volumetric geometry would have to be achieved. Following research into the various Grasshopper forums where examples of definitions were present, it became apparent that the simpler the parameters that could be inputted, the better for an exercise such as the one being undertaken in this thesis.

Correlation between Excel spreadsheet and definition was critical. Through research a definition generated by Bill Allen at Evolvelab appeared to appeal to the task in hand. The definition itself was aimed at a healthcare facility where high adjacencies were present and it seemed that this definition would be a great starting point to assist with completion of phase 1 of the design element of this thesis.

Upon accessing the definition and example file, the definition at first glance appeared overtly complex and even contained an evolutionary solver using Galapagos plug in, which for the purposes of this exercise, was a step ahead of where The Conversion of the data within the DLC data sheets allowed.

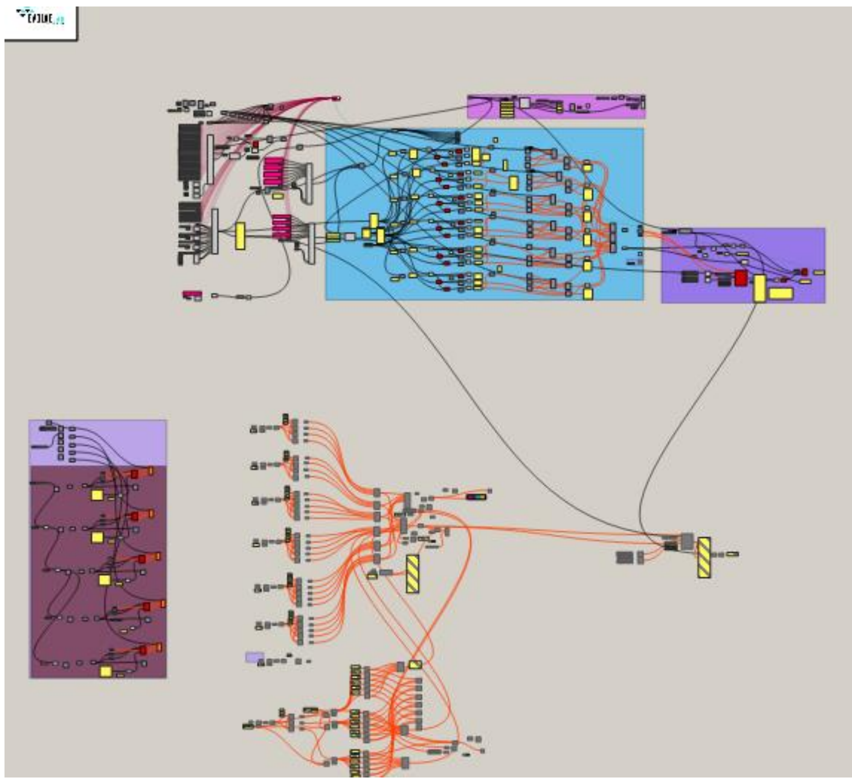

Figure 13: Evolvelab's Definition for High Adjacency Healthcare Facility

However, upon running the definition and evolutionary solver, it appeared that a range of commands within were requiring debugging, upgraded and even downgrades of various components owing to the version of Rhino/Grasshopper they were created in. The writer was using Rhino 7 but some definitions were created using Rhino 5 or 6 with various adaptations required to even get the geometry shown in the example file. This task was extremely labour intensive, especially trying to reverse engineer a definition, which as impressive as it appeared, could be analogised to deconstructing a 1980's electric powered milk float to try to get it to run when you have a Tesla in the garage. All of this before trying to input the DLC data into a new Excel document and getting the definition to run.

This sample definition used an excel reader and had a building programme, complete with an adjacency matrix in excel format. The assumption was that by replacing the existing data for room sizes / adjacencies etc that definition would generate the geometry at the very least. Regrettably the cumbersome and complex nature of this old definition did not compute any of the DLC data and after much deliberation with the Thesis supervisor and contributors to the Grasshopper3D forum, it was decided that the best cause of action would be to create a definition from a blank canvas where the level of complexity could be simplified but agile enough to evolve as the level of detail that is required increased.

Following the Perkins + Will journal referenced in the literature review, it was felt that focussing on simple programming of geometry rather than full Space Planning Optimisation was a better starting point which is where LMN Architects Tech Studio was discovered following further research. Yet again an overtly complex definition was kindly shared but one which despite the lack of narrative and doubtful comments by Scott Crawford: Principal of the Tech Studio*: "It's been a while since we've done anything with this work, but maybe you'll still find it useful. That is if it still works"* made it feel like history would be repeating itself and that the previous hypothesis of starting from scratch was the best course of action.

However, once the definition was accessed, there was less amount of debugging required, and the skills learned during the debugging of the previous definition actually made the interpretation of the LMN Architects one easier to understand and dissect, meaning elements in the definition that were irrelevant in to the generation of each room by representation of a conceptual mass could be eliminated altogether, giving rise to customisation and tweaking to suit the requirements of Design Phase 1.

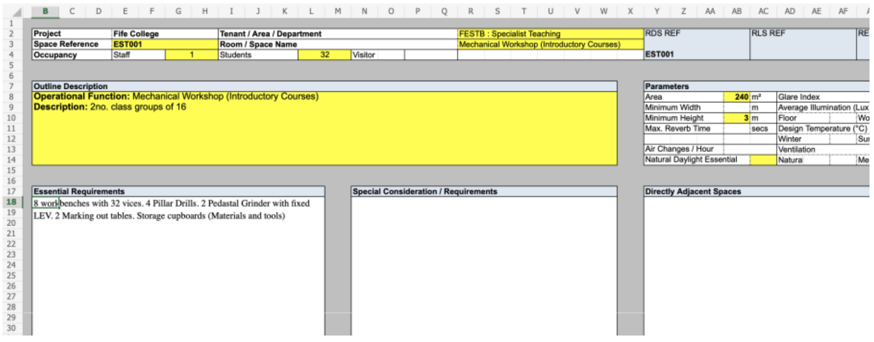

Figure 14: Example of DLC Datasheet (see appendix folder 1)

To begin with the DLC data was converted to a new spreadsheet against the following parameters:

- Department
- Room Type
- Room Name
- Room Number
- Quantity
- Length
- Width
- Height
- Program Area
- Colour

The definition created via the excel reader would find the spreadsheet column that has the closest match to the above names. The major advantage to this is that additional Columns can be added within the format Programme Data cluster giving rise to mass customisation from plant to day light requirements, although acknowledgement given to issues of being too data rich and complex for a proof of concept task.

	DEPARTMENT	ROOM TYPE	ROOM NAME	ROOM NUMBER	PROGRAM AREA	QUANTITY	TOTAL AREA	Height	Length	Width	Color
2	Construction and Engineering	WORKSHOP	Mechanical Workshop (introductory Courses)	EST001	240	1	240	5	15	15	Green
3	Construction and Engineering	WORKSHOP	Specialist Controls	EST002	40	1	40	5	8	5	Green
4	Construction and Engineering	WORKSHOP	Electrical Engineering Workshop incorporating Electrical Installation and	EST003	120	1	120	5	15	7.5	Green
5	Construction and Engineering	WORKSHOP	Electrical Engineering Workshop incorporating Electrical Installation and	EST004	120	1	120	5	15	7.5	Green
6	Construction and Engineering	WORKSHOP	Electrical Engineering Workshop incorporating Electrical Installation and	EST005	120	1	120	5	15	7.5	Green
7	Construction and Engineering	WORKSHOP	Engineering Workshop	EST006	120	1	120	5	12	8	Green
8	Construction and Engineering	WORKSHOP	Engineering Workshop	EST007	120	1	120	5	12	8	Green
9	Construction and Engineering	WORKSHOP	Engineering Workshop	EST008	120	1	120	5	12	8	Green
10	Construction and Engineering	WORKSHOP	Fabrication and Welding Workshop	EST009	120	1	120	5	15	7.5	Blue
11	Construction and Engineering	WORKSHOP	Fabrication and Welding Workshop	EST010	120	1	120	5	15	7.5	Blue
12	Construction and Engineering	WORKSHOP	Digital Advanced Manufacturing	EST011	120	1	120	5	12	8	Green
13	Construction and Engineering	WORKSHOP	Machine Workshop	EST012	120	1	120	5	12	8	Green
14	Construction and Engineering	LABRATORY	Whitlock Lab (Renewables)	EST013	120	1	120	5	15	9	Orange

Figure 15: Excel Building Programme Data (see appendix folder 1)

By linking the data, the *Format Programme Data* command was then used to interpret the data and sort into boxes, thus converting numerical data into geometry. Customisation of the arrangement of the geometry was a useful option, enabling users to determine arrangement of building programme to suit particular requirements of a HUD. For this exercise, columns were sorted by department but this could be done by room number, volume etc.

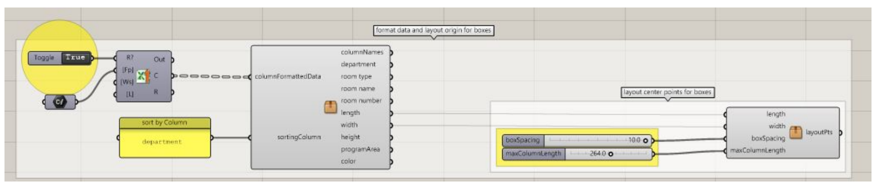
Figure 16: Resulting Geometry from Excel Data

As previously mentioned, columns in the excel spreadsheet themselves could be customised in line with the definition as seen in FIGXX. Whilst the focus for this exercise was relating space, geometry and description, the columns themselves could reflect items such as daylighting / sound requirements, giving tailored solutions to meet primary objectives of a building programme.

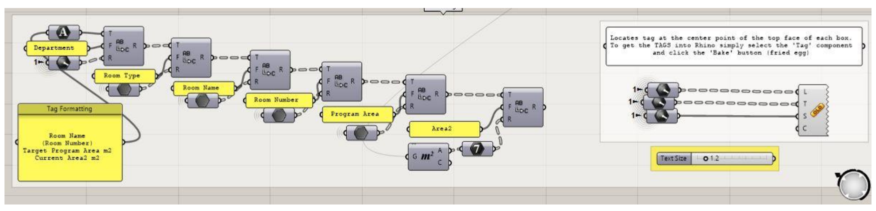
Figure 17: Definition Showing Tag Formatting for Excel Columns

As well as the arrangement of columns, the definition on FIGXX arranges data from the building programme into geometrical shapes, inheriting the key dimensions and colour schemes defined in the building programme excel document.

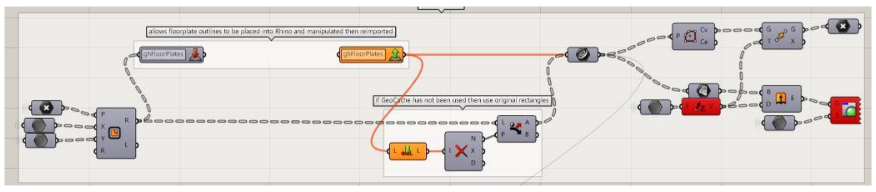

Figure 18: Definition Showing Floor Geometry

This then results in the creation of the geometry by means of a series of masses to give a HUD that emphasises the collective masses as individual components.

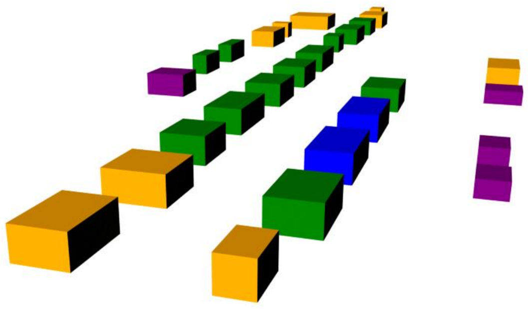

Figure 19: Resulting Blocks Following Baking of Definition

In addition, the grasshopper definition inherits the attributes from each column, displaying them in a visual display than can support user identification of each space and the critical project parameters. From an end user / client perspective this helps interpretation of space and information but from a designer's point of view, this relates to basic fundamentals of CAD defined "Block Attributes" typically synonyms with early adopters 3d CAD software. In more recent times this information can integrate with typical BIM processes where workflows exist between platforms at various stages in a design process. There is no limitation in terms of what information may elected to be present within the attributes, however, interoperability and workflows must be determined to allow this information to be read and interpreted correctly, otherwise it is a static label with no meaning. The use of excel and numerical data in particular is a huge advantage in this sphere for visual programming language interpretation.

Figure 20: Blocks With Room Information Tags

Autodesk define generative design as a design exploration process. Where designers or engineers input design goals into the generative design software, along with parameters such as performance or spatial requirements, materials, manufacturing methods, and cost constraints.

By taking the steps already described in this thesis, the generative design process has taken simple data into a visual programming language in Grasshopper, producing static elements with basic attributes. Naturally in the design of a building these elements will have interrelationships and affinities / adjacencies but if it was possible to assemble these without those constraints at present to develop a conceptual mass, client and designer would begin to get a feel for scoping design permutations.

This process could easily be conducted manually by baking the grasshopper definition and using CAD commands in rhino to move the masses into an assembly. However, the purpose of generative design is to automate that process by determining parameters critical to the objectives of the project in hand. To that end, exploration of further grasshopper plug-in's to assemble the masses within a defined area was to be explored.

Many contributors to the Grasshopper 3d forum advised against this method as there would be a heavy reliance upon phyton scripting and programming. However, a plug in was discovered called PackRat which is a bin packing component where containers (masses) can be assembled using defined boundaries (containers) as well as obstacles to be avoided.

First assumption was to convert the masses created from the excel document into Boundary Representations (BReps) to then feed into the PackRat component.

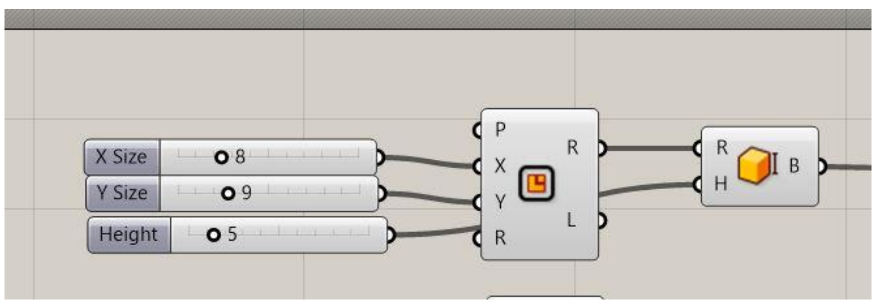

Figure 21: Box Rectangle Geometry definition

The PackRat component did not appear to compute the BReps meaning the volumes has to be created manually using Rectangle and Box rectangle geometry tools where the room volumes were programmed. This was labour intensive given the manner in which the volumes had been created and in hindsight, converting the data from Excel into masses that are readable in PackRat would have saved time and effort in that respect.

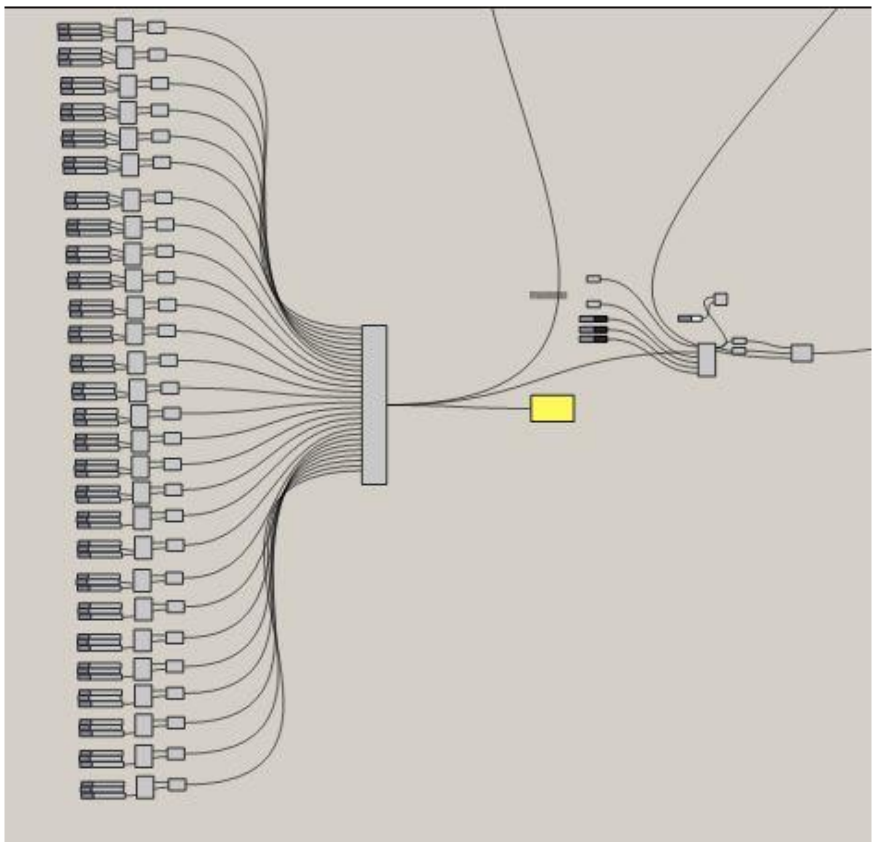

Figure 22: indicating Merging of Geometry to PackRat

However, after these were created, merged then entwined, PackRat sorted these into a series of boxes , all of which had the same origin coordinates.

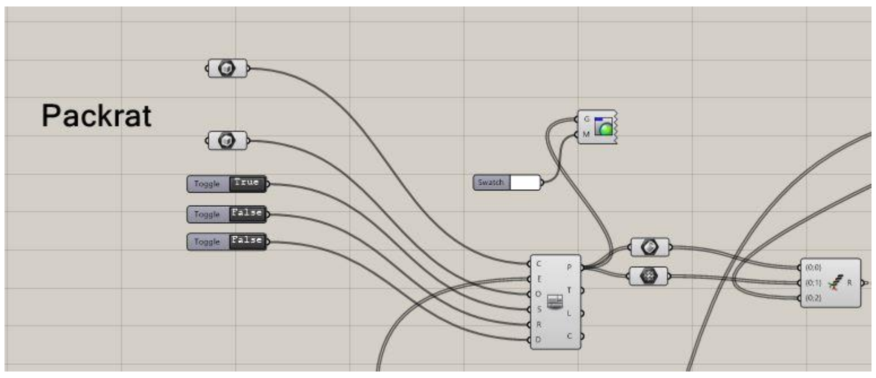

Figure 23: PackRat Definition

Once the PackRat toggles were commissioned, the boxes were then packed within the container, where an obstacle to represent an atrium, gave the PackRat component a constraint to work around rather that the mundane rectangle container.

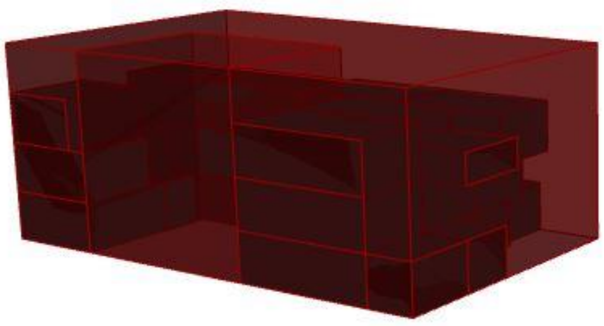

Figure 24: Container with Obstacle and Masses Stacked Within

Figs 24 represents the container, obstacle and boxes packed within whereas Figs 25 and 26 indicate the masses assembled to indicate a simple building form.

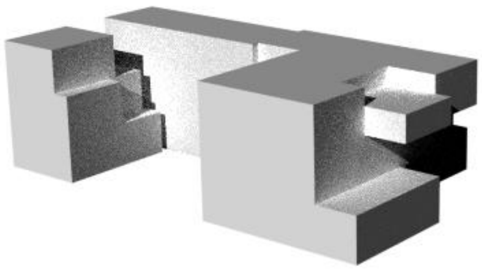

Figure 25: Resultant Building Mass View A

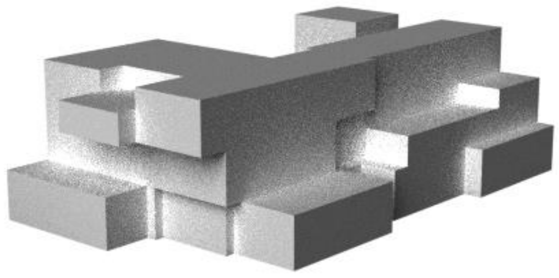

Figure 26: Resultant Building Mass View B

3.4 Chapter 1: Parametric Design Phase 1 Summary

Considering the timescale taken to generate the conceptual mass in this exercise by comparison with manually generating using drafting tools, one could be forgiven for choosing to disregard the immediate advantages of visual programming for the creation of a design concept. However, given the infinite amounts of data that can be customised into a programme and as we look toward phase 2, having a building programme that is linked to an automated design process means that simple changes in room size, adjacencies or any other parameters deemed critical during the conceptual design stage, can lead to efficiencies during design development and into technical design. Furthermore, given the opportunity to customise data that is centric to the project, will enable designers to utilise this within an integrated BIM ecosystem where further visual programming can be utilised to evaluate and simulate the implications of design decision. Again, the key and benefit to this is context of the customisation. For this exercise, the focus was purely on volume, space and obstacles, restricting the effectiveness of but also demonstrating the potential available.

On reflection, the variety of design tools available via grasshopper plug ins can perhaps murk the waters for a designer with limited capabilities in relation to visual programming which is a skill traditionally overlooked in many undergraduate AEC programmes. A designer with novice skills in this sphere may waste too much time debugging as well as creating definitions that may not work, this at the expense of critical design time. With this in mind, the scope of a design team must extend to include persons with digital skillsets that can enhance design development, simulation and analysis as the benefits to this can be realised once familiarity and efficiency with digital design tools are realised.

An objective of this Thesis is the federation of estates building over more than one site. The complexities involved in generating this are becoming apparent through Phase 1 but the ability to enhance data sets with items such as space utilisation in existing facilities is an additional parameter or fitness objective that can be customised to bring about efficiency.

Phase 1 has been extremely useful in creating a new building mass. An audit of an existing building estate can subsequently be programmed in a similar manner within excel then using grasshopper definitions. Whilst spaces may have to be manually assembled rather than packed to emphasis a true reflection of an existing asset, the ability to begin using evolutionary solvers to configure room adjacencies across various building based on factors deemed critical for the purposes of a particular project opens up the possibility of federation of mass amounts of data.

Without getting too carried away with what can be achieved at this stage, a cautious approach for Phase 2, sticking to the principles of using small amounts of data that can be programmed will still be crucial in order to demonstrate a proof of concept and only then can potential be identified as well as a pathway to get there.

3.5 Chapter 2: Parametric Design Phase 2

A key function of multi parameter or multi objective optimisation (MOO) design tools is to support early design development to create high performance buildings. [11]*MOO is a parametric and generative design methodology which enables the rapid exploration of alternative options and the computational assessment of trade-offs between environmental performance, energy consumption and capital expense.*

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[11] Xiaofei Shen1, Aman Singhvi1, Andrea Mengual1, Maria Spastri2, and Victoria Watson2. 'EVALUATING THE MULTI-OBJECTIVE OPTIMIZATION METHODOLOGY FOR PERFORMANCE-BASED BUILDING DESIGN IN PROFESSIONAL PRACTICE', 2018. https://www.ashrae.org/File%20Library/Conferences/Specialty%20Conferences/2018%20Building%20Performance%20Analysis%20Conference%20and%20SimBuild/Papers/C088.pdf.

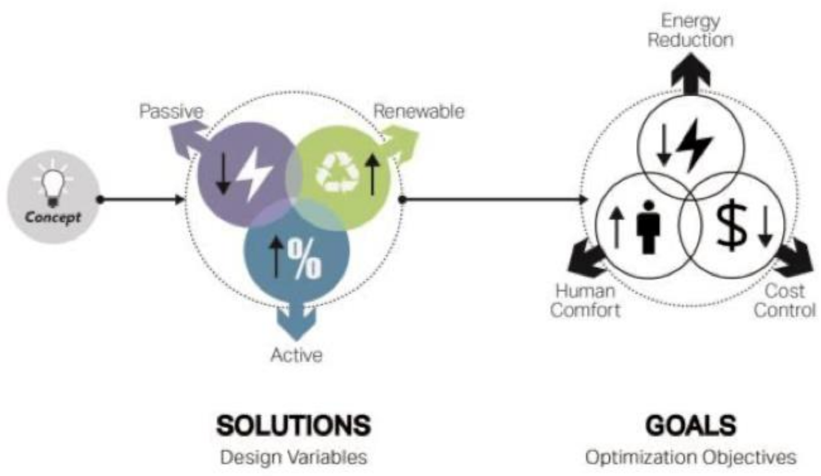

Figure 27: Example of Design Conflicts

Often design criteria can conflict, causing repeated design iterations between stakeholders' requirements which can be both time consuming and costly in the early stages of a design project, meaning MOO can be a critical process and tool to bring greater efficiency to the design process through reducing decision making and design time whilst encouraging greater collaboration between all stakeholders.

The process enables a potentially exhaustive exploration of design solutions in a fraction of the time and with greater accuracy by using numerical data to simultaneously optimise more than one objective set against pre-defined constraints.

The consensus in industry is that evolutionary algorithms, also known as genetic algorithms, will significantly improve the computational effort required for MOO and will allow designers to address a wider range of design problems (Attia et al, 2013).

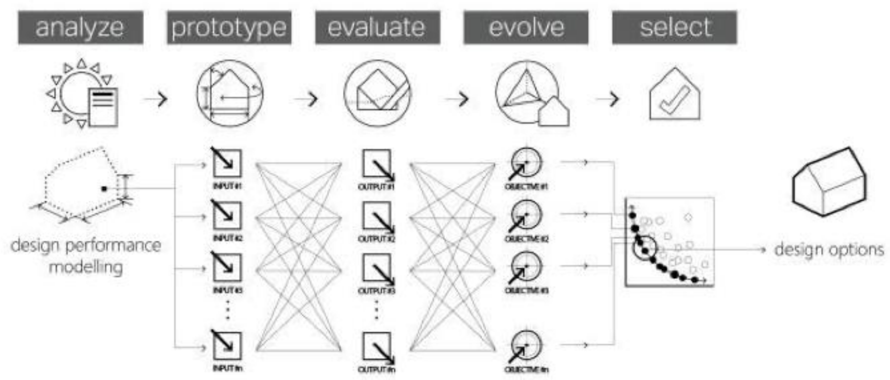

Figure 28: Xiaofei et al's Proposed Workflow for MOO

Xiaofei et al suggest a 5 step workflow be adopted through the phases of architectural design: Analyse, Evaluate, Evolve, Select, in the case of MOO, the ability to set objectives and identify problems through thorough analysis, should help support what parameters should be considered when undertaking generative design.

Hypothetical objectives for the DLC can be set. Many factors can be considered such as massing dimensions, envelope properties, cost and even energy systems. [12]*However, the speed at which a design solution can be found through the MOO methodology depends on the computational power available to the designer and the ability of their tool to effectively manipulate the input parameters.*

With this in mind and considering the thesis is working to a proof of concept, basic objectives will be set with a view to evaluation of the process and opportunities for enhancement / further development identified during data analysis. Objectives to consider for the DLC design optimisation could be from the following:

- Optimise best solution for adjacencies
- Smallest building footprint over 3 storeys
- Maximise external surface area to attract natural light
- Minimise upper floor levels
- Maximum / minimum density
- Identify duplicate facility types

Whilst these objectives are not exhaustive, they will require to be programmed using appropriate software and contextualised to the DLC building created in Design Phase 1 to be deemed reliable and relevant to the objectives of this thesis. Other objectives relevant to energy and net zero could be considered but the level of detail in the conceptual model is very basic and would require further development to be at a level where material properties and systems can be analysed.

Parametric modelling software will again be required to generate prototypes and the intentions are again to use Rhino / Grasshopper. Following research and discussion with thesis supervisor, the Wallacei X evolutionary engine is proposed to be used to run the evolutionary simulations.

[12] Xiaofei Shen1, Aman Singhvi1, Andrea Mengual1, Maria Spastri2, and Victoria Watson2. 'EVALUATING THE MULTI-OBJECTIVE OPTIMIZATION METHODOLOGY FOR PERFORMANCE-BASED BUILDING DESIGN IN PROFESSIONAL PRACTICE', 2018. https://www.ashrae.org/File%20Library/Conferences/Specialty%20Conferences/2018%20Building%20Performance%20Analysis%20Conference%20and%20SimBuild/Papers/C088.pdf.

Wallacei X employs the NSGA-2 algorithm (Deb et. al., 2001) and is being used because of its ability to be set up to analyse a design problem that can generate analysed outputted results, allowing users to select the desired solution or solutions for the final output.

Upon further research it is apparent that Wallacei simulations for large scale design problems and parameters can take days to compute as well as reliance upon sufficient hardware. This may hamper efforts to conduct the suggested design problems in the manner intended and the risk of Rhino crashing is a strong possibility if the design problem is complex. A cautious approach is to be adopted by considering simplification of the design problems or as they are referred to in Wallacei "fitness objectives" and this will at the very least support a hypothesis for consideration and reflection in the conclusion of this architectural thesis around the potential for more complex parameters to create more generative solutions to the wider design problems for tertiary educational estates.

Whilst Wallacei is the evolutionary engine that is being proposed, others can be considered:

- [13]***Galapagos –*** *Out-of-the-box Grasshopper-based evolutionary solver*
- ***Octopus****– It allows the search for many goals at once, producing a range of optimized trade-off solutions between the extremes of each goal.*
- ***Optimus –*** *new metaheuristic optimization plug-in for Grasshopper.*
- ***Opossum****– two of the best-performing single-objective optimization algorithms in Grasshopper*
- ***Biomorpher****– Allow designers to engage with the process of evolutionary development itself.*
- ***Design Space Exploration –*** *These tools aim to support visual, performance-based design space exploration and interactive multi-objective optimization (MOO) for conceptual design*

The major advantage Wallacei has over many of the evolutionary engineers mentioned above is that it its highly detailed analytic tools can cater for multi objectives rather than single objective, creating an infinite amount of generations of designs, with supporting data and standard deviation grids within the one component.

The success of Galapagos as an engine has provided some precedence for single objective but the purpose of this thesis is support a hypothesis that generative design can help estates where multi objectives have to be considered in order for data to be presented that assist design, in use as well as federation of information from a range of sources.

3.6 Chapter 2: Parametric Design Phase 2 Results

Design Phase 1 saw the creation of bin packed conceptual mass that represented an assembly of all spaces that were identified in the building programme. With this assembly being generated randomly with defined boundary and obstacles, the ability to create an optimised solution based on fitness objectives will allow a series of permutations to be created. To that end, the previous definitions that were created in Design Phase 1 will be inherited as a base point for the execution of Design Phase 2.

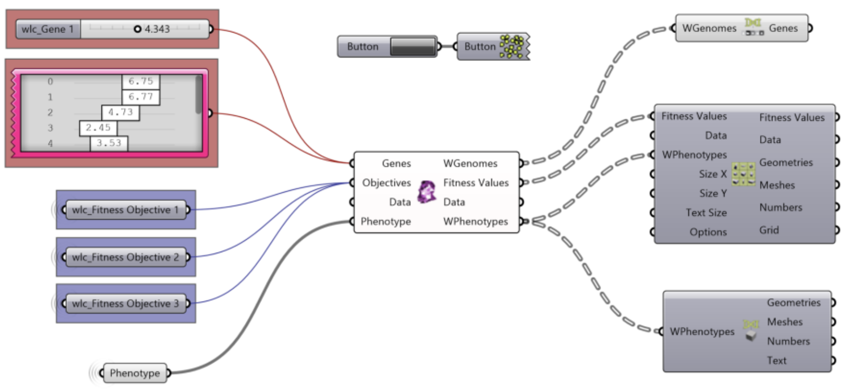

Figure 29: Wallacei Component Example

Wallacei requires a series of inputs in order to run simulations of design variants. Genes are created from sliders and Gene pools and will ultimately be the numerical inputs that generate the variables. In addition to that, fitness objectives are required which will require grasshopper definitions to determine the values that will be used to programme the optimisation. The Phenotype is essentially the mass that was generated in Design Phase one.

Reflecting on Design Phase 1 and the debugging required to interpret a previously concluded definition, the approach to undertake this again was considered with caution. However, despite the previous experience of undertaking this, it was critical to enable an understanding of the mechanisms that would allow the Wallacei component to run so a sample definition was first assessed (Wallacei Tutorial Grasshopper definition) to establish what level the definition would have to aspire to be in order to work.

What became clear, that to allow the definition to run, and maximise its potential, Fitness Objectives would have to be established. Given aforementioned evidence of data rich models causing Rhino to crash, it was decided to use two fitness objectives and two that should not require too much computation power nor be overtly complex to determine the possible solutions.
The chosen objectives were: **Maximise the Differences Between Heights** and **Minimise the Volume.** Given a precedence context was used to determine the objectives, definitions were created which would allow simple assembly's of the conceptual mass to be generated with minor variants.

[13] https://provingground.io/2019/11/19/free-generative-design-a-brief-overview-of-tools-created-by-the-grasshopper-community/

For the first Fitness Objective: **Maximise the Differences Between Heights**, the *Gene pool* tool was first introduced which forms the basis of the numerical matter to run variations of the differences in height for which the building can be within the container. Using the *relative difference* component to assess these values and differentiate, this was then computed as a *result which when coupled with mass addition* and *One over X* was then connected to a *number* component with the prefix *wlc_Maximise the difference between height.* The importance of this was Wallacei to recognise the numerical input for this particular definition which would then be identifiable as a Gene.

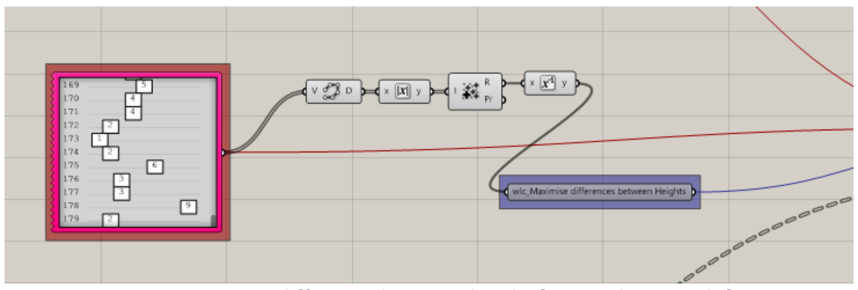

Figure 30: Maximise difference between height fitness objective definition

The second Fitness Objective: **Minimise Volume** involved a similar process by connecting a *Gene pool* to again give the numerical matter to convert variables. This component then used the geometry from the *merged fields* from the boxed geometry which then computed the m2 from the *area component* which was then *multiplied* to a result. This was the dispatched into *target lists* followed by the *mass addition* component. Once again the *numerical component* was the used to identify the definition as a Gene, using the prefix wlc_Minimise Volume.

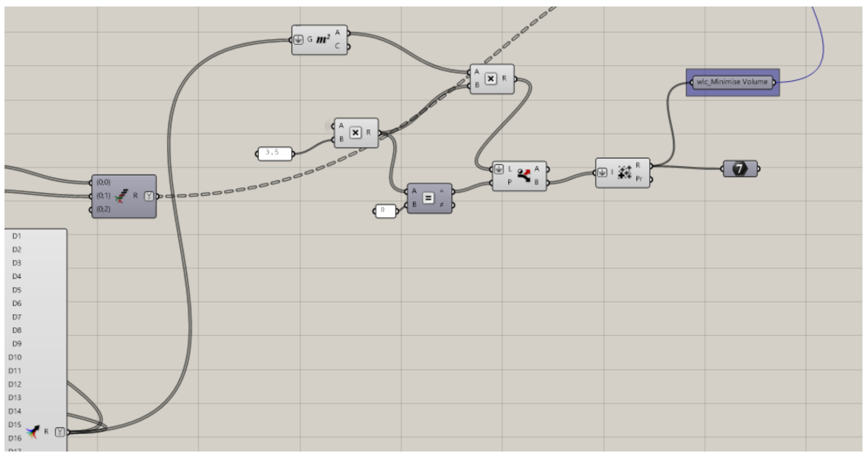

Figure 31: Minimise volume fitness objective definition

The last input for this exercise centred around providing the geometry or Phenotype. This task utilised the entwined PackRat definition to give bin packed geometries which the design variables are then programmed to differentiate within Wallacei.

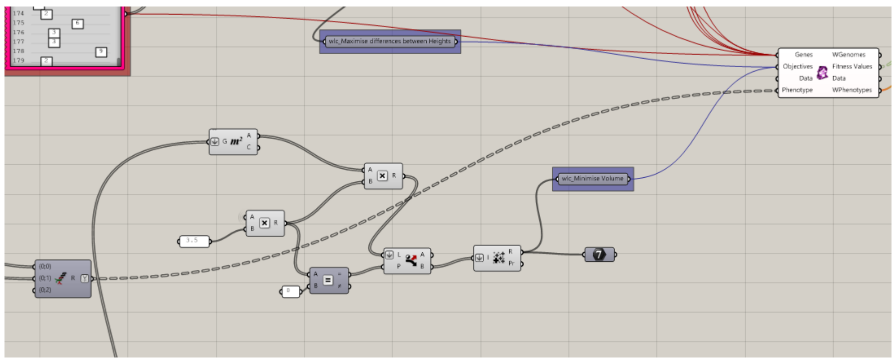

Figure 32: Geometry linked to phenotype in Wallacei component

With all definitions connected to the Wallacei component, the first task was to run the evolutionary simulation. In order to set this up, the Phenotype was required to be disabled, given the evolutionary engines reliance upon numerical data, the geometric data could cause Rhino to crash, allowing the evolutionary solver to drive the generations and populations prior to exporting the chosen generation to the phentotype which would then give a range of design permutations, the quantity of which would be determined by analysing the selection.

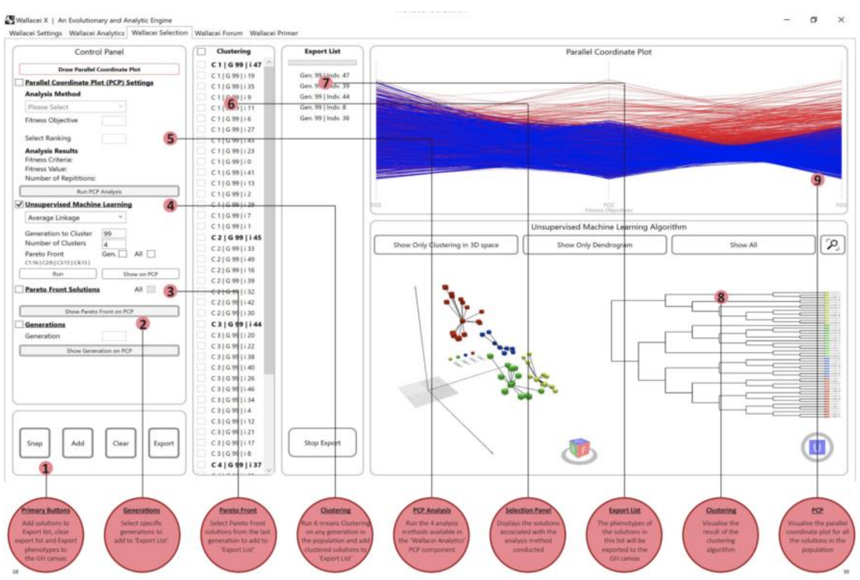

Figure 33: Maximise difference between height fitness objective definition

Upon commissioning the first simulation, it became apparent that there was an issue within the definition that leaded to the Wallacei component. No simulation results were found, yet no traceability of or errors were present within the grasshopper canvas meaning that a painstaking trial and error debugging process had to occur. During this time and countless endeavours later, it appeared that the one of the Genepools was not connected directly to Wallacei but was solely attached to the Minimise volume element of the definition, once this was then attached to the gene within Wallacei it eventually run a full simulation, based on the creation of a generation size of 50 with a generation count of 100 which gave a population maximum population size of 5000 permutations.

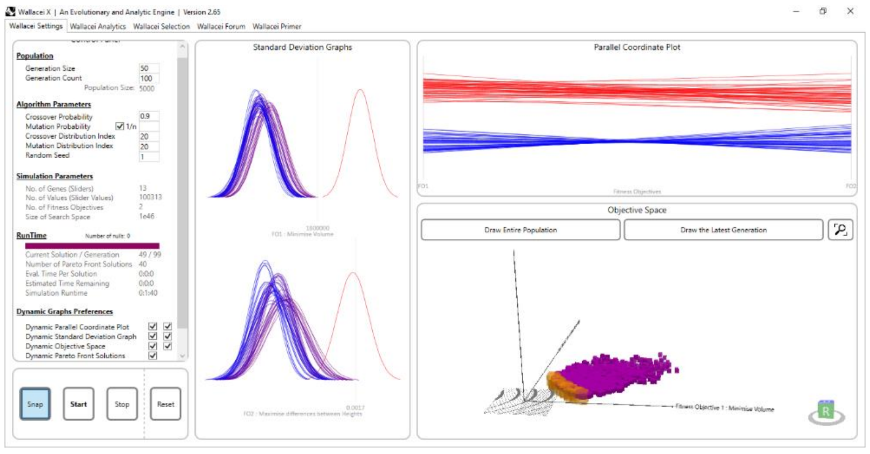

Figure 34: Wallacei Interface showing standard deviation graphs

Within the Wallacei interface, Standard deviation Graphs first indicate the populations for FO1 (Fitness Objective 1) and FO2.The displays works on the premise that sharper the curve the less value that solution offers the objective so flatter curves would naturally give a more desirable solution for the solution. The entire population of variants can be represented on the Objective Space graph which again gives a good visual indicator to the most suitable solutions to meet the objectives. Of note, by adding a 3rd fitness objective, this would then represent the solutions in 3d form.

Moving towards the Analysis chart, particular solutions were able to be identified by rank, matching with the particular fitness objective so optimum solutions could be numerically called. Naturally selecting a range of good, bad and in different solutions would give a base for comparison. What is important for designers at this phase is to begin prioritising fitness objectives to take precedence, clearly the more fitness objectives, the more parameters that can be optimised meaning design time is spent assessing the best solutions. With only two fitness objectives, the variants and proximity of solutions can be closer, meaning that despite having ranked solutions, there may be several that would fit the criteria. Again, adding more fitness objectives would help extracting the most appropriate solution.

Again, thinking of the further objectives of creating additional estates in a federated system, objectives could be considered that indicate a duplicate facility in the sister building. At this stage in the thesis, that is perhaps a consideration following meeting the first two initial fitness objectives, rather than overly complicate and make the solution data rich whilst trying to demonstrate a proof of concept.

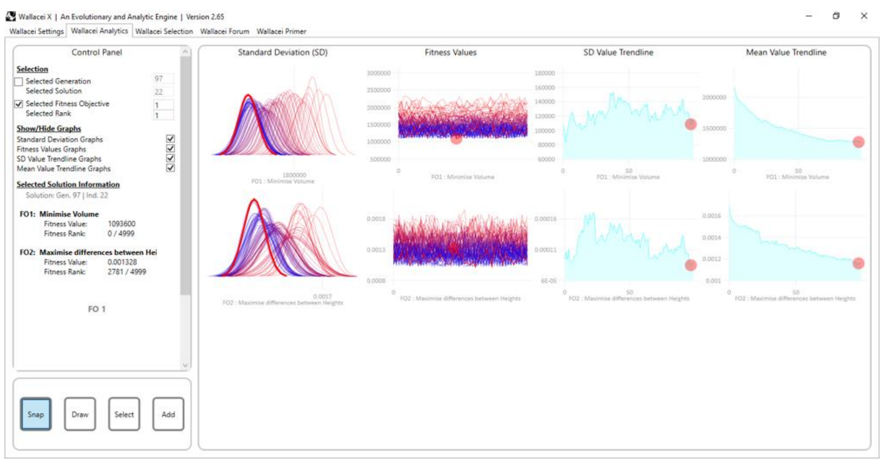

Figure 35: Wallacei Interface Analysis chart showing graphs and selection criteria options

Wallacei's main export features are in the Selection tab where generations can be clustered against a range of parameters, again emphasising the customisation potential. Selected clusters and linkages can be illustrated in 3d space and a dendrogram, to illustrate the hierarchy of solutions and their rank towards the fitness objectives. This is a useful visual tool that can allow design teams to see rank and assess solutions based on their relationship with other solutions and meeting the fitness objectives.

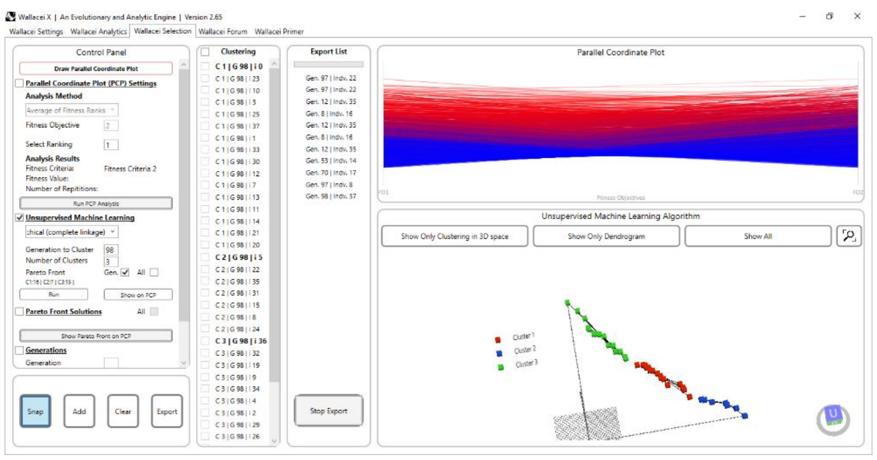

Figure 36: Wallacei Interface Selection showing 3d space and dendrogram with export lists

Upon selecting the genes to export, a modest amount were collectively selected to demonstrate a range of solutions from highest to lowest ranked. As Wallacei's evolutionary solver computes variants based on the fitness objectives, the Phenotype is added once the simulation has run with the design variants presenting themselves in Rhino.

The simplest way to get a HUD of the design variants is to add the Wallacei *Distribute to Grid* component and connect the Fitness Values and WPhenotype as well as customising the grid spacing and text.

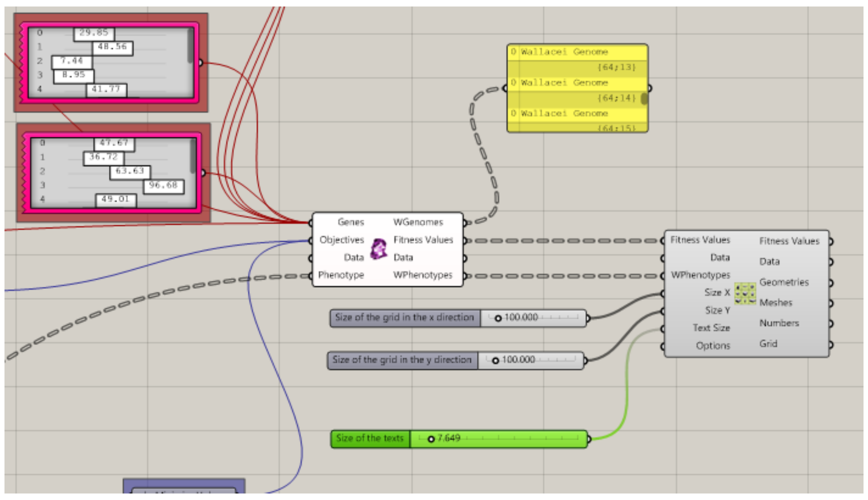

Figure 37: Wallacei Distribute to Grid component

Once this was enabled, the design variants appeared in Rhino, complete with generation number and fitness objective ranking in a grid structure. Upon closer inspection, it appeared that every design variant had the exact same form despite the different fitness values and generations indicating otherwise.

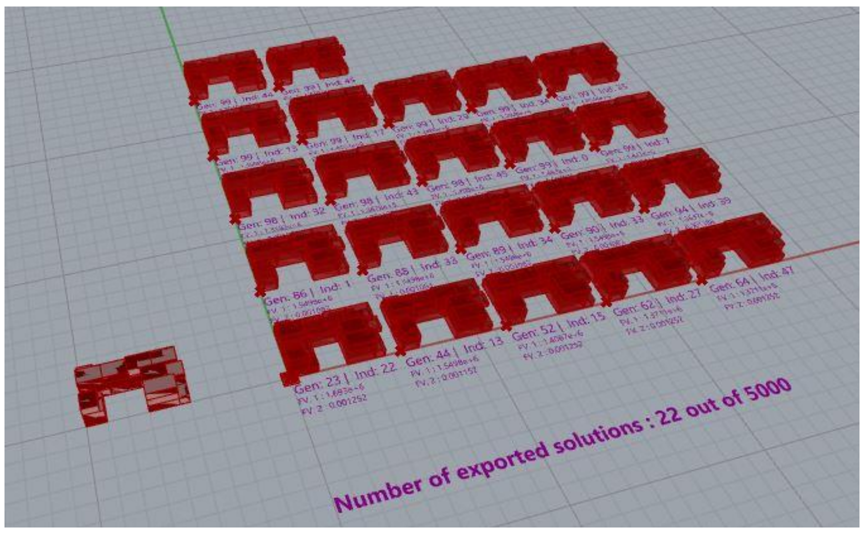

Figure38: Identical Design Variants

This naturally presented a problem in achieving the fitness objectives and indeed design variants. The next logical step was to evaluate the definition and ensure all geometrical and numerical data was computing through the definition and arriving at the same points. Drawing reference to previous simulations, using other components, various conversions of geometry from BReps, to Meshes to Numerical data was considered and tried but made no difference to the design permutations.

Yet again, another painstaking process was underway to evaluate the definitions to try and de-bug where the issue may be, resulting in further time lost trying to fix the problem. Putting this into the context of a design and estates infrastructure team, clearly time spent trying to fix/de-bug is lost design time, leading to questions about the mainstreaming of a solution to a design problem that is highly specialised and fragile in terms of its intricacies.

Many attempts were made conclude to the design task, including setting only one fitness objective for optimising but regrettably this could not be achieved. During this exercise, it was considered that PackRat itself may have actually solved the problem by computing the volumes into the container in task 1 which indicated that PackRat itself was an actual fitness objective so a last attempt was made with the definition and gene pools added to give the opportunity to vary but yet again the task came back with cloned variants leading to somewhat disappointment.

At this stage, it was decided to seek alternative precedents to back up the hypothesis of multi objective optimisation design tools in the use of tertiary education estates infrastructure.

Figure 39: Further design variants following PackRat single objective definitnion

3.7 Chapter 2: Parametric Design Phase 2 Summary

Disappointingly the objective and aspiration of design phase 2 in terms of creating federated building models of two facilities that can be programmed to give design permutations based on the needs of each facility was not achieved. Whilst an attempt was made to meet this objective, the exercise in itself was useful from the point of view of understanding the complexities of data manipulation within a visual programming context as well as the opportunities that multi objective optimisation can present to design problems.

Reflecting on the process undertaken in the execution of Design Phase 2 of this thesis, the opportunity to re-visit this from strategic perspective would perhaps see a different approach taken. Given that single objective optimisation tools such as Galapagos and Opossum exist, it would perhaps have been more appropriate to focus on single objective optimisation in the first instance, using these solvers to ensure the basic fundamentals of the grasshopper definitions for each fitness objective were working more accurately prior to attempting Wallacei.

Whilst this may seem an unnecessary, duplication of endeavours, what it would allow is an easier way of troubleshooting any issues with individual objectives prior to a cumbersome definition being built with a view to Wallacei solving everything! Whilst that is Wallacei's function and purpose, it must be noted that the complexities of adopting a visual programming methodology to compute a design solution is not necessarily a mainstream tool and the overwhelming reverse engineering required when a possible solution goes wrong can lead to inefficiencies in the design phases of a project. This is despite its obvious uptake amongst the more advanced architectural practices in the world and the major advantages to the wider design community.

According to Willis and Woodward (2010), "parametric modelling remains best suited to organize technical knowledge related to a building's geometry or construction system." However, what is abundantly clear is that technical knowledge of a building is its data and not its geometry and this exercise was an excellent opportunity to use raw numerical building data to generate a form which sadly did not achieve design permutations but demonstrated the opportunity that exists when thinking of a building programme using numbers and algorithms generate a permutation that is effective in its geometrical output and order.

Of note, customised and tailored solutions can be developed to ease user friendliness and remove the visual programming complexities that exist but also directly target the fitness objectives or design problems associated with a project. The team at Proving Ground who are behind many grasshopper apps such as Conduit are believers in a data-driven process, having assembled many grasshopper workflows. They highlight the potential for leveraging data and computation for a better built environment and even adopt the term "Software Development Kit" (SDK) to signal the growing connection between the *algorithmic design tools that they make and what that they create with them.*

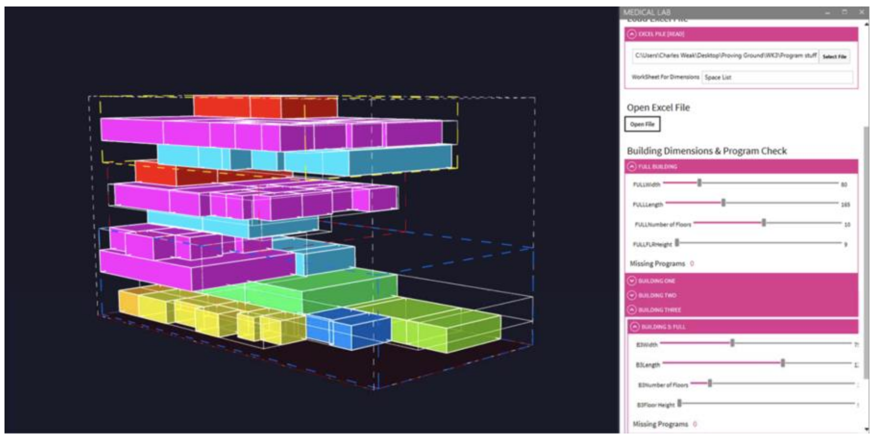

Figure 40: Proving Grounds Human UI Component skin

This approach has even seen a Program Visualization Tool not too dissimilar to the process undertaken in Design Phase 1 which also uses Excel data and PackRat to bundle together program into its most compressed building form. The data from excel and geometry work behind the scenes within grasshopper where the Human UI (User Interface) component provides a skin that allows the boxes to be manipulated using simple user friendly control panels, removing the visual programming complexities for an end user. It is this approach that will appeal to design teams and end users which helps support the hypothesis of the effectiveness of generative design tools being used to interconnect and federate existing and new tertiary education estates. The ability to customise using the Human UI component will allow this to be mainstreamed to suit the specific needs and objectives of any organisation.

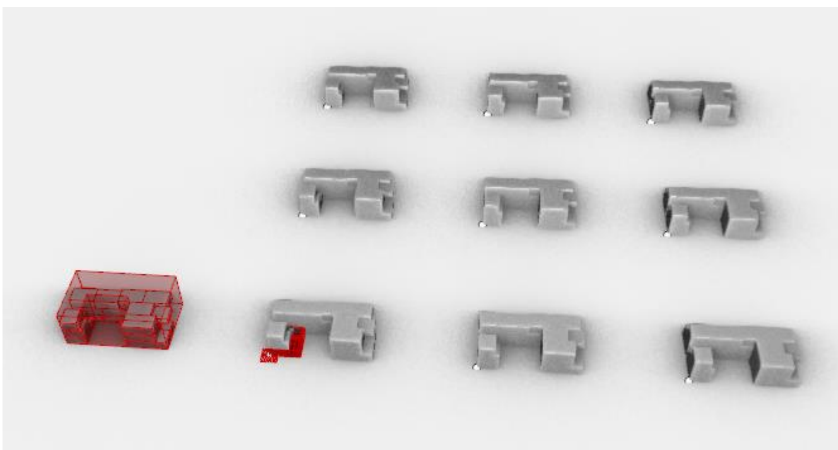
Figure 41: Wallacei failed design iterations

4.0 Conclusion

The Coherence Review of Tertiary Education as well as The Scottish Governments Infrastructure Investment Plan provide a clear opportunity for the coherence of physical estates and infrastructure for skills and training providers across Scotland. As has been covered during the literature review, government capital spend on new build physical infrastructure will be discouraged in favour of repurposing facilities providing another reason to make estates between institutions more coherent.

Already, regionalised partnerships are forming, an example being the East Central Scotland Colleges Collaboration (ECSCC) between Fife College, West Lothian College and Edinburgh College where opportunities for joined up thinking are present. Whilst the focus may well be on the coherence of curriculum and delivery, the opportunity to understand each others' physical infrastructure and estates availability / requirements is an opportunity to begin creating an interconnected, federated estates audit with a view to optimising asset utilisation between the colleges.

The ability to collate data on every asset used in the sector is an enormous task but one that every centre should be able to provide. However, as this thesis has demonstrated, a standardised approach to data collation, in the context of an Excel spreadsheet for this thesis, provides the opportunity to create an ecosystem that has asset information for each centre. This can be achieved from very day to day tools such as Excel that are familiar tools to asset management staff. To do so requires the creation of a network of practitioners, an example being nominated estates staff from ECSCC to collate this data driven task. The opportunity to scale and share more asset information is one that has limitless boundaries although as this thesis has identified, tools that are used to compute the generative designs will require refinement and smaller portions of data be piloted before institutions can begin to dream of the endless possibilities.

The use of Excel to programme and create a building mass using visual programming such as the PackRat component of Grasshopper is a workflow that created the first stage of static data becoming live through its use in the generative design tools. Evidently the complexities of visual programming tools to typical AEC professionals let alone estates staff requires an interface and customisation of tools which allow users to manipulate and edit the programme without having to revert to python scripting and grasshopper definitions. The SDK tools adopted by Proving Ground offer degrees of customisation for end users through the Human UI interface and to generate a tool that asset managers can use, in a user friendly interface would increase the appeal of collating and federating data for asset managers. This concept also applies to the alignment of adjacencies and affinities of technical education facilities which this thesis also identified as problematic owing to the complexities of visual programming and de-bugging / upgrading software to ensure a definition runs correctly. Ownership and use of this tool should not be the sole responsibility of estates staff but should be an iterative tool where project knowledge is shared and edited amongst all stakeholders as the PRISMApp tool identified in the Literature review impressively showcased.

In tandem with the Scottish Governments Infrastructure Investment Plan, future needs assessments are required to begin the process of funding physical infrastructure. The opportunity exists for the tertiary education sector to begin that process by collating and federating data on their physical estates and infrastructure. The ability is there to align that with fitness objectives such as curriculum planning and regional skills assessments, thus creating a connected ecosystem with efficient workflows between systems, institutions, sector bodies and government. This thesis has identified that the tools to do exist via multi objective optimisation such as Wallacei to allow this to happen. However, customisation of fitness objectives that are inherently critical to demonstrate the effectiveness this tool can have for the sector requires further scoping. In addition to that, making the interface more appealing, thus reducing troubleshooting and increasing user-friendliness gives this vision the best chance of being realised using multi-objective optimisation design tools.

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