OPTIMISING HARBOUR TYPOLOGY IN THE FORM FINDING PROCESS USING COMPUTATIONAL DESIGN: A CASE STUDY OF A GREENFIELD PORT FACILITY

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Abstract. The bulk of computational design strategies and research have been focused on issues related to architectural form and building systems. This is done by employing computational tools to optimise architectural forms, building performance and generally, improve quality of living. Many of these methodologies are based on the concept of form finding - varying geometric elements to generate and evaluate options to derive optimised solutions. However, beyond building designs, the concept of form finding can find its relevance in other design applications too such as engineering, landscape, and in our case, the design of ports, or more specifically harbour typology. In most building scenarios, the plot of land earmarked for development is typically selected beforehand, hence little exploration have been done to optimise land topology, when in fact the profile of land is the governing feature in most designs. For performance driven facilities like ports with high economic and political impact, there is value in optimizing topology to maximise throughput. Through the multi-disciplinary and collaborative effort of stakeholders and specialists, our project explored optimizing harbour topology via performance-based approach using computational design. The phenomenon, including impact and effects of trade-offs, are discussed and presented in this paper through a case study of a Greenfield port facility.

Keywords. Form finding; form optimisation; port masterplanning; harbour typology; computational design.

1. Introduction

1.1. USING GENERATIVE DESIGN FOR LAND USE MASTERPLANNING FOR PORTS

Looking beyond architectural form and building systems which the bulk of computational design strategies are focused on (Belesky, et al. 2012), the concept of form finding and form optimisation (Colakoglu 2005;2010;2011) which many of these computational designs are based on, may also find relevance in land use master planning, especially for performance driven facilities like marine ports where its productivity is driven by its capacity and efficiency (Ligteringen 2017). In other words, shape of land (and sea) directly affects performance of ports in terms of vessels' manoeuvrability and port capacity, as generation of land restricts sea space affecting port throughput, and generation of more sea space impedes land workflow and efficiency. Restrictive conditions like these act as interacting variables, defining a design space that sets the boundaries for any speculative explorations (Bunster 2013). Even as designing of ports is not new, harbour typology have not evolved significantly and little have been explored on the relationship of land and sea spaces in computational design, presenting much opportunities in this area.

1.2. CASE STUDY

The development is a real-world case study where the client seeks to construct a multi-purpose port facility on a Greenfield site in Singapore. The study consists of front-end planning, and if assessed to be favourable, to lead up to detailed design and land reclamation for construction of the harbour. In such early stage of planning, the client finds computational design useful for investigating the solution trade space, with the objective of finding the best harbour profile optimised for their port operations. This is the first time computational design is used for developing harbour profiles in Singapore. To help computational designers who are not familiar with the port planning process understand better, the client had arranged for them to participate in the user-engagement workshops held with various stakeholders as part of the study for understanding the port planning requirements better. The workshop seeks to develop the overall strategic plan and outlining functional and performance requirements. This helps to establish spatial needs and sets the plan up towards stakeholder driven instead of only expert driven to improve quality of the plan (Kunze & Schmitt 2010). The computational designers will later work with the port planners to scrutinise and translate the requirements into computational parameters.

2. Methods and Results

2.1. OVERALL DESIGN PROCESS

The design process takes reference from established master planning guides for port facilities, which are guidelines used widely in the marine industry (MarCom WG158, PIANC 2014). Guided by the conventional port planning process as well as requirements established by the stakeholders, the overall computational process was then set up to expand the solution space (i.e. form finding) and then optimizing generated solutions (i.e. form optimization) to distil the best performing profiles. The steps include (1) setting requirements, (2) generation of harbour profiles, (3) testing feasibility of options, and (4) sense making of results. This process fundamentally replicates the conventional port planning process but is tweaked to adapt to computational design methodology. This is to help stakeholders draw parallel to the process they are familiar with, an important consideration when employing computational techniques through a collaborative effort to gather meaningful inputs.

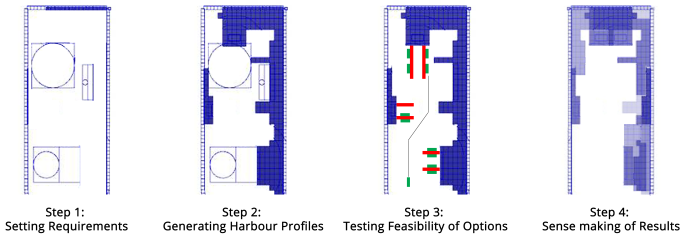

Figure 1. Overall Design Process.

2.2. STEP 1: SETTING REQUIREMENTS

In early stages of port master planning, spatial requirements are set at high level, relating mainly to navigation, berth orientation and location, hinterland connections and stakeholder requirements (MarCom WG185, PIANC 2019). In the computational design process, these requirements are set as initial parameters and are used for generation of options in the form finding process and evaluation of options in the form optimization process. For this port facility in Singapore, the client has focused mainly on navigational requirements for driving the harbour design.

- Spatial Requirements. The client intends to set aside 60% of the plot for sea and 40% of the plot for land, with the possibility of ±10% variation in space allocation. Sea spatial requirements were gathered at this stage where clients require adequate sea space for maintenance yard and small craft facility. These requirements are later used as key criterion in the computational model as part of the form finding process, where the land area is used as upper limit during the generation of harbour profiles.
- Design Vessels. The client provided a list of vessels planned to be berthed in the facility, with the largest vessel expected to be received at the port facility to be 200m, length overall. To cater for flexibility, the computational model was set to optimise profile edges towards 200m in length to create “modular berths” to allow the vessel the ability to berth anywhere.
- Turning Circle. Within the basin, it is required to cater clear sea space for vessels to manoeuvre safely during directional change. This translates to a minimum clear turning circle radius within the sea basin. In the computational model, this was used as one of the criteria for generating harbour profiles.
- Berth Orientation. Based on the land parcel, port planners have derived various berth orientations that were viable. These orientations are used for generation of piers in the computational model for berthing of vessels. Ideally, vessels navigating within the harbour should not deviate too much from the original path to travel to assigned berth, especially for larger ships. This consideration was coded in the algorithm for testing the feasibility of profiles in step 3.

2.3. STEP 2: GENERATION OF HARBOUR PROFILES

To maximise solution space, two methodologies with varying degree of freedom were employed for generation of profiles. (1) Parametric Modelling, and (2) Grid-Based Generative Approach. These approaches are part of the form finding process to generate as many different profiles as possible, prior to testing these options in the form optimisation process.

2.3.1. Parametric Modelling

In parametric modelling, the form finding process was performed by modelling interface between land and sea (i.e. the shore) as parametrically defined associative geometry, and varied to generate profile options. In this case, the parametric variables of the model are based on land depth, and by varying the land depth on the parcels to its North, East and West to generate land profiles. The algorithm considered total land and sea area of the profiles, where profiles beyond the requirement (i.e. 60% sea, 40% land) are not shortlisted.

2.3.2. Grid-Based Generative Approach

In grid-based generative approach, discrete grid cells are used in the form finding process and optimised using genetic algorithm based on performance criteria to obtain top performing options. Firstly, “obstacles” representing the sea spatial requirements are assigned on random within the boundary. These include the maintenance yard, turning circle, small craft facility etc. Then, land parcels represented by modular grids (i.e. 40m x 40m) are “spawned” on random to form the land mass. The intent behind assigning “obstacles” prior to generating the profiles is to increase the fitness of the options, as the grid-based generative approach methodology could generate indefinite number of options and to filter the best performing options would take up too much computing power and too much time. This is as shown in Figure 2, where “obstacles” are assigned in random positions and land mass are generated around these obstacles to form the profiles.

Figure 2. Land Mass Generated around “Obstacles” to Form Profiles.

The profiles generated will then form the initial population to be optimised using genetic algorithm. These profiles are optimised based on evaluation criteria developed together with the client, set as genomes in the algorithm, including “clear basin area”, “land edge length”, “land contiguity” etc. This is to favour profiles with open basin spaces for manoeuvring and longer edge length for higher utility of shoreline such as allowing wharf berthing of vessels. The weightage for the evaluation criteria were ranked based on Analytic Hierarchy Process (AHP), a technique client find fitting for such multi-criterion complex problems, as they were able to breakdown the requirements in a structured manner to organise their priorities. In the application of computational design, the technique was also useful for contextualising priorities to develop numerical weights for single-objective optimisation to derive a final fitness score.

Top performing options are then shortlisted for feasibility testing. Figure 3 shows the profiles generated using the two approaches organised by fitness scores in early optimisation stage, whereas Figure 4 shows the profiles as more optimisations are employed. It is worthy to note that with more generations, the grid-based profiles improve in performance over the parametric profiles, and gradually converge to a common profile across the top performing profiles.

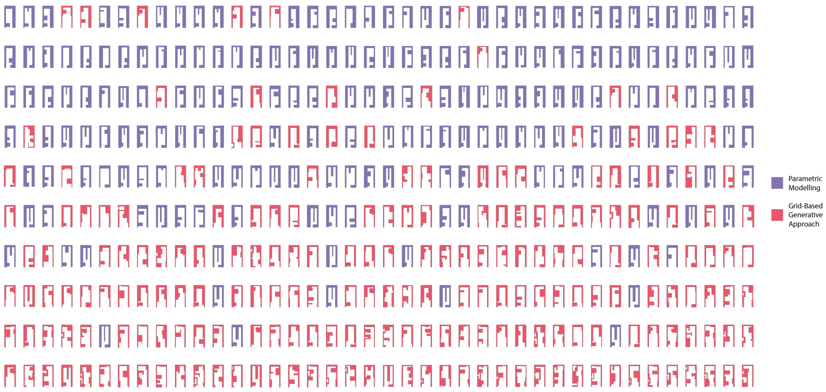

Figure 3. Profiles Generated using Parametric Modelling and Grid Base Generative Approach.

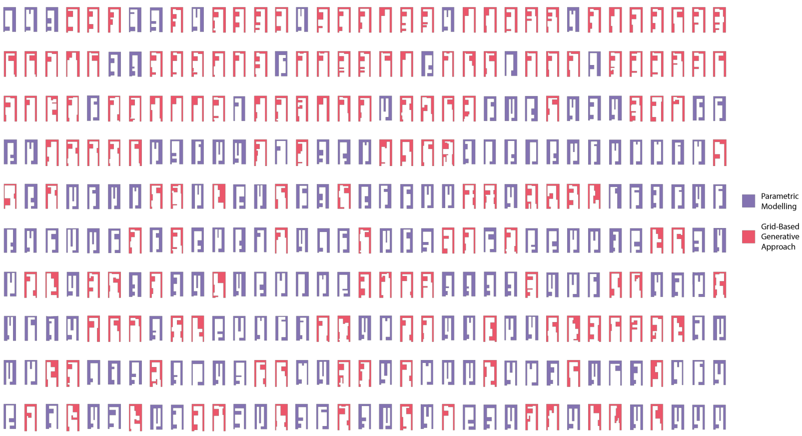

Figure 4. Optimised Profiles with More Generations.

2.3.3. Adapting Computational Models for Client's Understanding

While the Grid-Based algorithm was set up to also generate profiles similar to Parametric Modelling, it was observed that the client had difficulties in drawing parallel between the algorithm and conventional port landuse planning process and was unable to associate the profiles for actual port use. Hence, the Parametric Model was set up to provide that half step as the algorithm mirrors the port landuse planning consideration more closely, where the depth of land was normally used as a key parameter. This is an important consideration especially for clients engaging computational designers for the first time. Where computational design is normally considered to be more relevant in academia, these considerations could help clients understand the subject better and achieve better 'buy-in' to the methodology.

2.3.4. Comparison of Approaches

The key difference between the two approach is in the form optimisation process. In Parametric Modelling, the form optimization process take place in step 3 during the feasibility testing to sieve out non-performing options. In Grid-Based Generative Approach, the optimisation process was intrinsically built within the algorithm, where genetic algorithm was employed to iterate the options to derive good performing profiles. As the discrete nature of Grid-Based Generative Approach sets the algorithm up to produce large number of non-performing options which could increase computational time in later steps, it was ideal to optimise the solutions up front in step 2. By employing genetic algorithm, higher population of phenotypes could also be set to further expand the solution space and be more exhaustive in considering all options using the same computational power. Employing the two approaches, the options were then brought into step 3 for feasibility testing.

2.4. STEP 3: TESTING FEASIBILITY OF OPTIONS

The next step of feasibility testing involves generating seaward facilities to simulate vessel approach to determine vessel manoeuvrability within the basin. This sieves out non-performing options that does not meet the operational requirements. The testing is a two-step process, including (1) generating piers of various orientation and (2) assigning vessels to the berths. For each option, calculation for the berthing length and angle of approach for each vessel assigned was recorded as its fitness score to determine the good performing profiles.

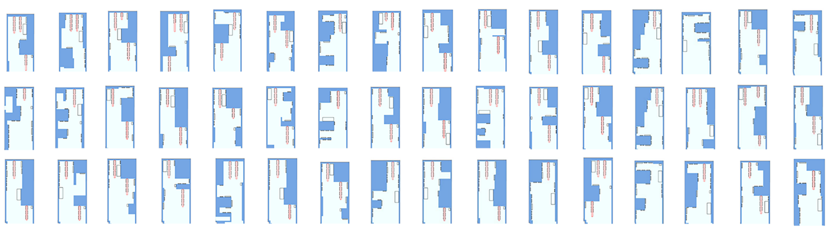

Figure 5. Profiles with Piers and Vessels Assigned.

2.5. SENSE MAKING TO DERIVE HARBOUR TYPOLOGY

Due to the extent of variability that is inherent with employing multiple layers of computational techniques, employing suitable methods for filtering data types was important to derive meaningful insights. For this case study, two methods of classification were applied, including (1) visual-based and (2) performance-based.

2.5.1. Visual-based Classification

As with conventional building typology, visual classification is a powerful tool for determining harbour typology. This was employed after Step 2 in the generation of harbour profiles, in an attempt to identify the most favourable type of land profile based on client's requirements. The profiles were categorised by location of land mass, with four main archetypes being identified: Inverted 'F', 'M' Mass, Multiple Mass and 'F' Mass. This categorisation effectively defines the vessels' navigational profile in the basin, one of the key considerations in master planning of ports. The profiles in each archetype were further superimposed to derive a common profile.

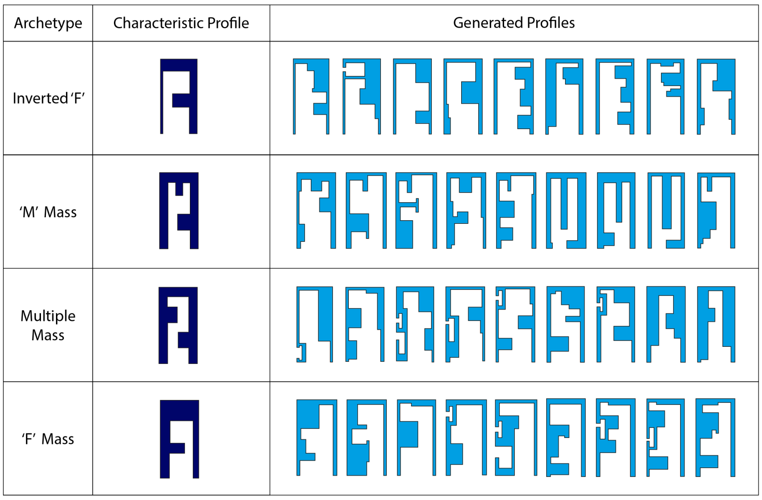

Figure 6. Harbour Profile Archetypes.

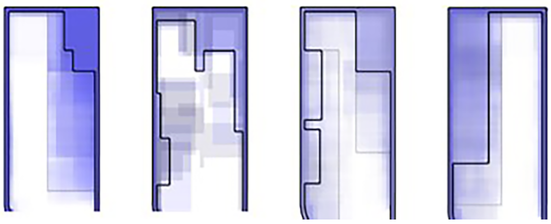

Figure 7. Heat Map to Identify Common Profile.

2.5.2. Performance-based Evaluation

The performance-based evaluation criteria were based on the AHP hierarchy developed earlier, but expanded to include criteria for vessel manoeuvrability from step 3. Tabulating the fitness scores computed at each stage, the final performance scores were derived. These scores were then used to shortlist the high performing profiles.

2.5.3. Sensemaking of Results

The two techniques were not used exclusively but in conjunction to draw insights from the results generated. After classifying the profiles by archetypes, we further ranked the profiles based on the fitness scores to examine which archetype performed better, and how changing the criteria weights would change the scores of the profiles. An average score for each archetype to represent the performance of the common profile was also tabulated. Client was able to see how changing their prioritisation would favour the type of profiles, and find this computational study useful to outline the flexibility of the land profiles to further validate their decision before conduct of any physical reclamation work, when it may already be too late. It was interesting to note that results were not always consistent, and profiles that looked similar visually could have very different scores. Understanding the logic and performing sensitivity studies would require more elaborate data crunching, as further discussed in Tan et. al (2020).

3. Discussion

The extent of complexity of the model and how harbour profiles generated led to diverging conclusions was fascinating. However, conflicting results and overload of data also led us to scrutinise and refine the process more, trawling through every parameter and constraint put in the algorithm to ensure meaningful results. Where required, we deliberately took a few steps back and adjust the algorithm to infuse more variability and filter better performing results quicker. For novel methodologies like this, there are no similar data to benchmark against to give clients the confidence they need (Tan, et al. 2020). Hence, it is useful to highlight trade-offs from varying priorities to aid clients in making informed decisions. This was well illustrated with the methodology.

Besides generating best performing options, the computational methodology also generated technically feasible but unconventional profiles which would not have been designed manually. For example, the model generated options such as dedicated small craft basin and multiple basins design, which when we presented to the client, thought were all feasible ideas that are worth exploring. This highlighted the degree of depth and breadth of solutions that computational models were able to bring to the table which deeply impressed the clients.

While the algorithm may be complex and challenging, we found most difficulties in Stage 4, as some of the results were found to be conflicting and we could not rationalise the behaviour behind. Therefore, there were multiple iterations with client on presentation of the results, and even just to agree on the best approach to move forward and conclude the study. Amidst the discussions, we also observed how clients were starting to lose trust in the methodology and how computational designers were losing their patience. Hence, mutual understanding is important in such collaborative efforts and both parties must manage their expectations.

Through the results, we could quantify how interacting variables between the spaces affected overall performance of the port. In this regard, the two spaces may be described as a ‘cross-disciplinary’ system with an interdependence directly impacting the outcome. By employing generative design methodology, it effectively simplifies the complex multi-level, multi-criterion form finding problem to distil insights and optimise spaces, even generating feasible profiles that presents different perspectives to bring about opportunities that could be missed if designed by hand.

For operational facilities like ports, our work on harbour typology is only the first step forward to outline the spatial needs. In early Masterplanning stage, it is important to provide maximum flexibility in laying out spatial geometric requirements to avoid excessive early investment (PIANC WG185 2019). To truly optimise operations for downstream activities, it is valuable to develop the computational methodology further to go beyond conceptual planning and include other considerations such as land operational workflow (e.g. land access, storage area, movement of goods), marine operations (e.g. berth turnaround time, tug operations), and environmental factors (e.g. harbour basin resonance, wave heights), of which are all directly influenced by the shape of harbour and basin.

4. Conclusion

Up till today, port master planning has been extremely tedious. Being a specialised trade involving high economic trade-offs, port designers and master planners are typically engineers with hydraulic training (Ligteringen 2017). They often are not exposed to computational design methodologies, which are more widely employed in architectural domain. What is presented here is only one case study. However, the methodology presented here is not limited to port facilities. These considerations captured are scalable for other complex operational infrastructure with interacting stakeholder requirements and clear throughput, including facilities such as airports, maintenance depots or production factories.

Just like in landscape design (Belesky, et al. 2012), there is a gap of unfilled potential for computational design techniques in port master planning, or even operational infrastructure altogether. Developing and distributing such techniques will empower designers and planners, leading to large payoff both economically and socially.

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