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Towards a Digital Twin of a Complex Maritime Site for Multi-Objective Optimization

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Possibilities for digital twin analytics and multi-objective optimisation within a complex maritime site

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Abstract. Complex maritime sites, such as ports and dockyards have a great variety of logistical challenges to be overcome on a regular basis, these challenges are usually distributed between several stakeholders each may have varying priorities. For some, it may be to achieve net carbon zero by reducing emissions and finding green methods to complete day to day operations, others may prioritise reducing cost, and then there may also be some who prioritise efficiency of movements within the site, reducing the amount of time it takes to complete tasks. These challenges are often solved by individuals making decisions based on their own priorities, this therefore may overrule the priorities of the site or other stakeholders. For example, while there are stakeholders making decisions to reduce cost regardless of environmental effect, the site would never achieve net carbon zero. These three priorities have been identified within Her Majesty's Naval Base (HMNB) Devonport, a complex maritime site in [redacted], [redacted] ([redacted]), and while they are conflicting, it is possible for the middle ground to compromise on each to find solutions which are acceptable across the board. Many stakeholders hold more than one of these priorities, however a choice must be made to compromise on these to find a solution. This article identifies a variety of logistical challenges for which optimal solutions can be found using artificial intelligence for conflicting priorities. This will aid the decision maker in finding a solution that meets their own priority, without abandoning other priorities held by the site and other stakeholders.

Keywords: Digital twin, visualisation, maritime logistics optimisation

1 Introduction

HMNB Devonport is one of three Royal Navy (RN) dockyards in the [redacted], and is currently home to two amphibious assault ships, half of the RN's Type 23 Frigates, two Trafalgar Class submarines, five survey vessels including HMS Protector, the RN's antarctic patrol ship, and will also be home to the new Type 26 Frigates which are currently under construction [1]. Additionally, HMNB

Devonport supports additional vessels such as visiting warships, Royal Fleet Auxiliary (RFA) ships and a fleet of decommissioned nuclear submarines. In addition to supporting these RN vessels, HMNB Devonport also supports the sailors on-board at HMNB Devonport through the provision of onsite barracks (HMS Drake) and associated facilities, and the delivery of training for the fleet through Flag Officer Sea Training (FOST) to both the surface and sub-surface fleet [1].

Due to the vast scope of what the dockyard achieves, there are many different organisations and teams actively working on specific projects. These 'stakeholders' comprise of a mixture of Ministry of Defence (MOD) Civil Servants, Armed Forces Uniformed Personnel, and external contractors. Babcock International PLC (Babcock) is the largest third party organisation on site, and they own a portion of the freehold of the site with the MOD owning the remainder. With so many different organisations and teams, it has been difficult to establish a development plan for the dockyard as each team works to their own individual project or contract which usually results in non-standardised approaches, and through the iterative development of the site, this has lead to the current site, which is now difficult to expand functionality due to the strains on many of the current systems. 'One Devonport' [2] is a new initiative to bring HMNB Devonport and Devonport Royal Dockyard (Babcock) together with a standardised vision and principles for all parties onsite. This has presented three key priorities for the base: reduce cost, increase time efficiency, and reduce environmental impact to aim for carbon net zero.

Optimisation is the process that finds the 'best' solution based on predetermined criterion. This solution may not be the absolute best solution, but at least a close approximate and without a full 'brute force' approach—which would take significantly longer to run—the actual best solution cannot be found. Using Artificial Intelligence (AI) tools such as Genetic Programming, the time required to find the optimum can be reduced while ensuring the found optimum is as fit as can be identified without the brute force computation. An optimisation problem requires a mathematical model, where inputs can be entered and the model produces a result based on the entered inputs, and it also requires the desired output from the model, or objective [3]. The computation would then take place which would test the model with a number of different input, each set would be a possible solution to the problem and the results from each test would be stored and compared with the desired outcome to give the solution a fitness value, how well it achieves the task. The solutions' fitness values can then be compared against each other to find the most optimal solution to the problem.

In the real world, many problems that require solving have many different objectives that all need to be considered when finding a solution, these are called multi-objective problems (MOP) [3]. This means that some solutions may be fit for some objectives but not others which results in the inability to provide a single 'best' solution because of the trade-off that typically exists between objectives. Multi-objective optimisation is the remedy for this shortfall. For example, when planning a route for a long journey, the planner may want to find a route that has the shortest distance, but also the shortest travel time. As roads have different speed limits, the route with the shortest distance may take more time to travel than a longer route with faster roads. If this problem was solved by a single objective optimiser, the shortest route would be found, or the quickest route would be found. However, whichever route is identified, the other objective remains ignored. There are many different approaches to multi-objective optimisation [4], however if both objectives are targeted in the same model, the result would be a variety of solutions which would be a compromise between the pre-set objectives. The planner in this example would then be able to select a route that is optimised for both distance and time, while not be the most optimum for either, the solution would be a good compromise for both.

A 'Digital Twin' is a virtual representation of a physical entity. A digital twin is an accurate model which can then simulate function for the entity, allowing parameters to be changed so that the effect can be predicted. The effectiveness of the digital twin relies on the accuracy of the model to the relevant level of abstraction for the specific problem that the twin is solving. Digital twin technology is emerging in a number of industries; some are very holistic, where the entity is a large group of physical systems, for example a digital twin of a building would have to model a variety of parameters, including physical dimensions, floor-plans, utilities and communication infrastructure, desk layout, personnel capacity and restroom facilities. Whereas a more specific digital twin may look at a specific machine as the entity where the machine would be in greater detail, but external details can be removed.

In this paper, the authors are treating the site of HMNB Devonport as the holistic entity for the digital twin, which in turn will then be used to analyse the current site to identify any potential vulnerabilities or areas for improvement. This bespoke digital twin can then be used as the model for the optimisation of MOPs within the site.

2 Modelling and Analysis for Optimisation

In order to find the optimal solution to a problem, the problem must first be identified, and then to optimise for this problem using optimisation algorithms, the problem must be modelled. Different possible solutions can then be run through this digital model to then produce a ranking as to how good that solution is and these rankings can then be compared to find the best solution.

Before optimisation possibilities within a complex maritime site can be discussed, the model must be discussed. For this scenario, the model in question will be a digital twin. This digital twin would be an up to date digital simulation of the entire site, parameters within the digital twin can then be modified by the optimiser and the result can be compared to the objective to give that solution a score.

HMNB Devonport is an old dockyard, and has been supporting the RN since 1691 [1] and has been developed iteratively over many years. This means that many of the problems may not be known. By creating a digital twin, the twin can analyse the current systems and infrastructure to be able to pinpoint any areas where there are single, double or triple point(s) of failure within the different layers of the site. For example, there may be, within the communications network, an active switch that, if powered down, would affect a greater portion of the site. When designing a new system, this would of course be taken into account, however because HMNB Devonport has been iteratively developed, there may be areas which have not been identified.

This digital twin would be able to identify these vulnerable areas within each layer of the site (buildings, roads, communications and utilities), the optimiser would then be able to produce a number of optimal solutions for rectifying these vulnerabilities. The digital twin would have three key separate functions.

2.1 Modelling

The digital twin must accurately model the function of the dockyard with the current inputted parameters. The accuracy of the model is vital to the successful impact of the digital twin; when the model is accurate, the user would be able able to adapt inputs and visualise the effect on the entity, across the layers.

2.2 Analysis

Once the model is designed to the current specification of the site, the digital twin can analyse the entity as a whole, and also each individual node within each layer. Looking at the effects on other nodes within the layer, and also other layers when a node is removed would then produce a report showing any single point of failure—a single node, that if is removed, would cause a drop of service for any other node within the site—which would be useful for identifying the problems to be optimised in the next function. These can be identified by removing a node, and checking that no other node becomes disconnected from the network, if a node is disconnected then the removed node is a single point of failure. After checking for single points of failures, the digital twin would be able to simulate the effect of a pair of nodes being removed, this would simulate each possibility of pairs within the site so would be a lot more intensive than looking for a single point of failure, but this would identify the pairs of nodes that would cause a double points of failure. To calculate the number of simulations required the Binomial Coefficient equation can be used, where n is the number of nodes, k is the group size and the result, C, is the number of possible combinations [5]. The Binomial Coefficient equation is

$$C(n,k) = \frac{n!}{k!(n-k)!} \tag{1}$$

Due to the nature of this model, the number of nodes, n, would be great; each building would be a node for communication and power, however buildings are not the only nodes required, there would be many more showing other critical infrastructure and as more detail is added to the model, nodes may be added within each building allowing for inter-building modelling and analysis. Therefore, to computationally solve this equation for these larger values of n, of which the factorial calculation above would timeout, there is a much simpler method of solving the same equation through the following function

```
def binomialCoefficient(n,k):
    c = 1
    n = int(input("Number of nodes: "))
    k = int(input("Group Size: "))
    for x in range(k):
        c = c * n
        n = n - 1
    f = math.factorial(k)
    C = c / f
    return C
```

Algorithm 1: *Binomial Coefficient Function*

Using the above function to solve the equations, if there was a digital twin with one thousand nodes, there would be one thousand different simulations to run, removing each node alone and monitoring the effect.

$$C(n,k) = \frac{n!}{k!(n-k)!} = \frac{1000!}{1!(1000-1)!} = 1000 \tag{2}$$

When looking for a double point of failure, the equation would be similar, however the total number of simulations to run would be significantly more.

$$C(n,k) = \frac{n!}{k!(n-k)!} = \frac{1000!}{2!(1000-2)!} = 499,500 \tag{3}$$

As the group size gets larger, the total number of simulations required also increases. Depending on the time required to complete a single simulation, it would be impractical to assess larger combinations for multiple points of failures. Below are the equations for triple, quadruple and quintuple points of failure.

$$\begin{aligned} C(n,k) &= \frac{n!}{k!(n-k)!} = \frac{1000!}{3!(1000-3)!} = 166,167,000 \\ C(n,k) &= \frac{n!}{k!(n-k)!} = \frac{1000!}{4!(1000-4)!} = 41,417,124,750 \\ C(n,k) &= \frac{n!}{k!(n-k)!} = \frac{1000!}{5!(1000-5)!} = 8,250,291,250,200 \end{aligned} \tag{4}$$

2.3 Optimisation

Using the digital twin as a model, problems identified through the 'analysis' part can be optimised for multiple objectives. Additionally, a problem could be manually input so the digital twin would then optimise a problem that was not identified through the digital twin analysis—this could be enhancing the effectiveness of an existing operation, or to plan the development of the site as discussed below in sec:op. Each MOP would be setup to ensure that the identified problem is solved, whilst also ensuring that the solution is compliant with MOD policies. Then three additional objectives would be considered, to ensure that the solution takes environmental impact, cost and efficiency into the model.

In this style of problem, there are two different types of target. Firstly, there are ‘constraints’, these are where a condition must be met, but once the condition is met, there is no requirement for a fitness rating. For example, with compliance with policies, the solutions would be compliant or not and if not the solution would not be acceptable. The other type of targets are ’objectives’, which are rated against their fitness for each objective, for example when optimising cost, there may be a budget so any solution over that value would be acceptable, however the solutions would still be assessed for fitness so they can be compared against each other. When looking at the problem to be solved, there would be an additional target, to remedy the problem, which could come under either type of target—objective or constraint—depending on the problem.

3 Optimisation Possibilities

HMNB Devonport is a large site, with lots of operations happening simultaneously and the infrastructure is relied upon to ensure that all current and future operations can take place so it is vital that vulnerabilities are mitigated and infrastructure is optimised to be robust and reliable. There are almost limitless optimisation problems that could be targeted within a large multi-faceted site such as HMNB Devonport, however, some have been identified and presented below within specific categories.

3.1 Infrastructure

HMNB Devonport covers over 650 acres of land and there are over 650 buildings on the site [1]. Many of these buildings are inhabited by teams who have historically held that building so they remain, however it may be more efficient for certain teams to be located elsewhere. By inputting the inhabitants of each building into the model and then identifying where they travel throughout the site and also what equipment they frequently use, the optimiser would be able to reassign teams to buildings to reduce the travel necessary. For example, the Traffic Management Officer (TMO) requires an office that is easily accessible as every person applying for a vehicle permit has to visit this office so the position is important to reduce the time that thousands of people have to spend travelling through the base each year to apply for a permit. After optimisation, it may be the case that this office is best suited to be in the middle of the base, however, it could potentially also be more efficient to place this office by one of the gated entrances to the site as the majority of the personnel would have to pass this location on entry to the site.

3.2 Utilities

HMNB Devonport is the largest energy consumer in [redacted] [6]. In the analysis phase, the digital twin will be able to identify where single points of failure are within the power network as well as the other utility networks (clearwater, greywater, blackwater and gas). Here, the digital twin wouldn't only be looking for areas within the power network that could effect the power network, but also nodes within the power network that may effect other areas. For example, there may be a building that is rarely inhabited, however it holds an active switch as a part of a communications network. The effect of this building going down may not be of great consequence to the power network, however the active switch would lose power and that could cause a large are of the site to unexpectedly loose connectivity. Connections like this being identified by the digital twin would allow for optimisation to occur to ensure that the site would not loose connectivity if that building lost power, and that the connection would remain through a different route.

3.3 Communications

Communications includes all data and telephony networks throughout the site, external data connections to the site, and also the wider defence network which hosts services for personnel to use at the dockyard. These networks are a prime choice for optimisation against single points of failures. With an iteratively designed network, it is possible for there to be an active switch, that if it went down, would cause mass outage across a large section of the site. This type of single point of failure would be held within the communications layer of the digital twin and the network could then be optimised to be more robust and mitigate the risk by adding backup routes for communication infrastructure whilst keeping cost and environmental impact down as much as possible. Additionally within the communications layer, if a building needs to be connected to a specific network, the digital twin could use multi-objective optimisation to provide a number of solutions that are robust, whilst also taking cost, effectiveness and carbon emissions into the fitness rating.

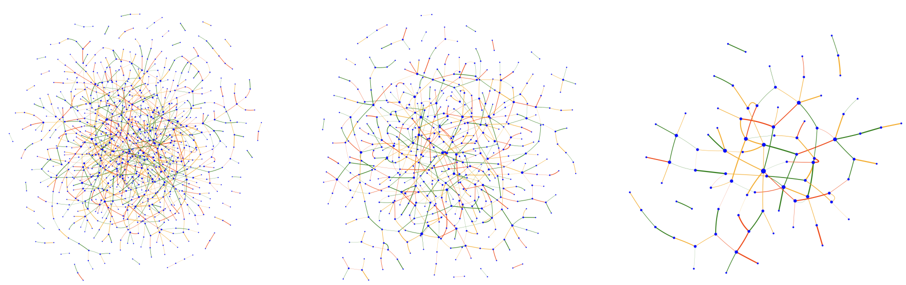
Due to the security nature of HMNB Devonport, the models referenced below have been separately generated based on random data created using the function in Listing 2 where the user can change the values for the number of connections—edges—and the number of nodes.

```python
def generate_data(nodes=10, edges=20):
    data = []
    rag = ("G", "G", "A", "A", "R") # RAG 1:2:2
    for i in range(edges): # for each edge get random data
        a = "N"+str(random.randint(0, nodes)) # start node
        b = "N"+str(random.randint(0, nodes)) # end node
        while a == b: # if start end node are the same
            b = "N"+str(random.randint(0, nodes))
        col = random.choice(rag) # select random RAG colour
```

```
        cor = random.randint(1, 36)*4 # number of cores
        data.append([i, a, b, col, cor]) # data to dataset
    data = pd.DataFrame(data, columns=["ID", "ANodeID", "
BNodeID", "Colour", "Cores"])
    data.to_csv("random_data.csv") # save data to .CSV file
    return data # return new random data for modelling
```

Algorithm 2: *Generate Random Network Data*

From this random data, a model of this network has been mapped using all relevant data, and can be visualised in an interactive HTML format. Below is Figure 1, showing the visualisation of three sets of random data as communication networks.



(a) *1000 Nodes* **(b)** *600 Nodes* **(c)** *100 Nodes*

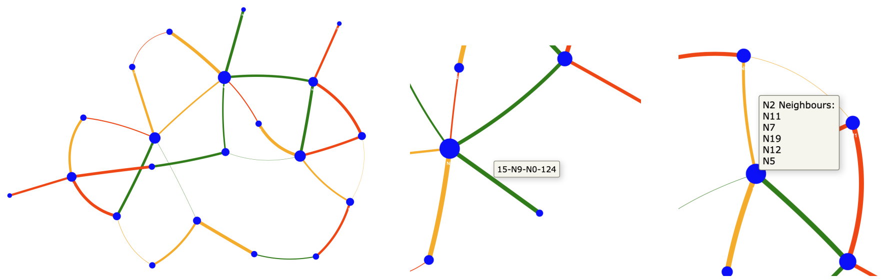
Figure 1: *Network Visualisations - 1000, 600 and 100 Edges*

These visualisations show each connected node as a blue circle, and the size of this circle is based upon the number of connections to that node. Each connection is then weighted based on the number of cores within that connection, the colour then represents the percentage of core that are available within that connection at the following tolerances

Red	**SPARE**<20%		**FAULTY**>80%
Amber	20%<**SPARE**<60%	**or**	40%<**FAULTY**<80%
Green	**SPARE**>60%		**FAULTY**<40%

Table 1: *Edges Colour Code - RAG*

As this has not be designed to be a communications network, these would be very inefficient and do not visually represent a real-world network so a much smaller representation, of only 30 edges, has been selected for further investigation as this appears to be closer to a feasible network design.



(a) *30 Nodes* **(b)** *Connections* **(c)** *Neighbours*

Figure 2: *Network Data Representation*

The visualisation then contains more information for the end user, each edge and node is labelled and, when selected, will provide further information. The edges will show a unique code for the connection, this code includes the edge ID, the start and end node IDs, and the number of cores in the connection; the node will show the ID of that node, and then IDs of each neighbouring node. The information provided for the edges and nodes are shown below in 2b and 2c respectively.

From this network map, analysis can take place to identify single and double points of failure, and once these have been identified optimisation can be used to provide a solution for these problems.

3.4 People

Many of the people who work at HMNB Devonport park their personal vehicle onsite. Parking permits are handled manually by the TMO and they provide parking based on the individuals requirements and eligibility. This, unfortunately, results in a less than optimal distribution of parking permits. Most of these permits are for a specific parking location, so multi-objective optimisation could optimise this distribution of permits to reduce the distance between people's parking location and workplace whilst keeping car parks under capacity.

4 Conclusions and Future Work

Through the use of a bespoke digital twin to accurately model and simulate the workings of a complex maritime site allows for almost limitless optimisations to take place. Each MOP solved by the digital twin would bring the site closer to their goals—whether this is through future development or improving current infrastructure—to reduce cost, environmental impact and improve efficiency whilst remaining compliant with MOD and commercial policies, as well as any other additional requirements for the problem being solved. In this article, the authors identified a small number of possibilities for optimisation throughout the complex site, but this is by no means an exhaustive list. Optimisation would be able to take place throughout any future works within the developing site as well as optimising current infrastructure and operations outside of the possibilities mentioned in sec:op. This highlights vast possibilities for optimisation within HMNB Devonport and other complex maritime sites and these possibilities could also be extrapolated through to complex sites outside of the maritime industry.

The next step for this research is to produce a proof of concept for this digital twin within a complex maritime site. Starting with a small number of parameters, the initial digital twin will model a small function of the site, starting with the communications network, and will then simulate for single points of failure, this will build from the current model of the network. Once any single points of failures are identified from the initial digital twin, the optimiser will be developed to provide a set of possible solutions for one of the single points of failure (if any are identified). A decision could then be made as to which solution is best depending on the fitness level of the solutions for each of the objectives. In addition to this, an upcoming step will be to gather real-life data from a non-confidential site so that the random data can be replaced with a real network, this will allow for publication of results and also prove the usefulness for this technology within a maritime site. These processes could then be repeated, each time adding more data to the digital twin, making the analysis more in-depth to identify problems which would be much harder to identify without a coherent holistic digital twin.

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Statements and Declarations

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