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

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Abstract: Her Majesty's Naval Base (HMNB) Devonport is a complex maritime site in Plymouth, United Kingdom (UK). Using digital twin technology, the authors will model and simulate the physical entity of the dockyard to optimize for a set of critical priorities. Digital twins are virtual representations of a physical entity, such as a vehicle. They can fully model a complex environment, accurately modelling individual layers within the entity, with each layer accessing data required from other layers. This results in an accurate simulation so that when changes are made in one layer of the model, the impact across the other layers may be observed. An end-user could interact with this digital twin to understand how changing input parameters would affect the measured outputs, allowing the end-users to simulate different options and compare the simulated outcomes before deciding a course of action. If the digital twin is of higher fidelity, the simulated outcomes would be more accurate and demonstrate potentially unintended effects allowing for a more comprehensive overview for the decision-maker. From this digital twin, a decision-maker can manually identify the best parameters to simulate the outcomes through the digital twin. However, using multi-objective optimization can reduce this process so that the twin can create the inputs, monitor the outcomes, and repeatedly try to produce a specific number of outcomes to choose from. These outcomes would be based on a few priorities initially set, and the optimizer would change inputs to enhance each of these priorities. At HMNB Devonport, three main priorities have been identified: cost reduction, time efficiency and carbon neutrality.

Keywords: *digital twin, visualization, multi-objective optimization, dockyard logistics*

1. INTRODUCTION

HMNB Devonport is a complex maritime site with many individual stakeholders. The site's purpose is to support the Royal Navy (RN) and its operations; to this end, the site requires more than purely service personnel. The Ministry of Defence (MOD) also assigns many civil servants to the site to manage and run various services across the site. However, public-sector employees are not sufficient to run and maintain the whole site, so a variety of contractors are required onsite, some of which are permanently based on site. Others are temporarily contracted to complete short-term projects. With all these separate organizations and smaller teams, there are many 'team leaders' and 'project managers', each focused on their priorities or role within the organization. The primary stakeholder is the MOD, and they own the freehold for much of the site. Another key stakeholder is Babcock International Group PLC (Babcock); Babcock owns the remainder of the site's freehold and holds the contract to maintain many of the RN's maritime assets. In each naval base, there is one stakeholder from within the RN, who is principally in charge on behalf of the MOD, the Naval Base Commander (NBC). Through conversation with HMNB Devonport's NBC, three key priorities have been identified related to all onsite operations. These are to minimize cost, improve efficiency and reduce environmental impact, aiming for net-zero emissions by 2050. Various government publications also mirror this. For example, Maritime 2050 [1] states that the UK will aim to be a role model in minimizing carbon emissions within shipping. The Department for Business [2] then states that emissions will be cut by 78% by 2035, adding that the long-term target has been enacted into legislation.

In addition to these priorities, Maritime 2050 [1] looks at technological progress as being vital for the future of the maritime industry, focusing on digitization and stating that 'the UK maritime sector will be "digital by default"' [1]. The MOD [3] has also given insight into the future of the RN, stating that investment will be focused on 'delivering a more modern, high-tech and automated Navy'. This process of digitization could begin by utilizing digital twin technology and optimization. A digital twin is an accurate digital model of a physical entity; in this case, it would be the dockyard, HMNB Devonport, and used to simulate operations to aid in risk management, planning maintenance and optimization. A digital twin would allow a complete understanding of the site's current performance and allow for a platform for planning and adapting future planning based on accurate simulated results. Optimization is the process of selecting the best solution based on a pre-determined criterion. There are many types of optimization; however, most have a single objective to optimize. For example, an objective may be to reduce the time it takes to do something, so the most optimal solution is the one that takes the shortest amount of time. One method of finding this solution is through evolutionary algorithms, which use natural evolution as a concept to improve solutions. This starts with a set of random solutions, which are then simulated and their effectiveness measured and given a fitness score. The highest scored solutions will then be used to create a new set, which will be simulated and rated, and subsequently compared with the original set, and the lowest scorers will be removed. This process will iterate many times, with mutations occurring where the solutions can continue to develop some new information to be simulated. This will finally result in a single solution that has the highest rating. If the objective is to reduce time, this would be the solution that results in the shortest time required. However, in many real-life problems, there is more than a single objective. It may be the case that the shortest solution would, in practice, cost much more than the second shortest, in which case the decision-maker may choose to compromise between time and cost.

This would be a multi-objective problem that would require three objectives to be considered, and multi-objective optimization algorithms would provide multiple solutions showing different compromises between the objectives. This digital twin could then work hand in hand with multi-objective optimization algorithms to have the digital twin provide the inputs for the model and then adapt those inputs over time until the best few solutions are found for the pre-defined priorities. The user would then be able to make an informed decision based on the results from many simulations, with each new set of inputs being created based upon the learning from the previous inputs. This would then provide solutions that take all priorities into account, while still allowing the user to select a solution according to their own focus. The use of digital twins in this way would not be limited to HMNB Devonport. It would also apply to other complex maritime sites, both military and commercial, and would be a basis for creating smart ports, where the digital twins could be formed using live data from around the port.

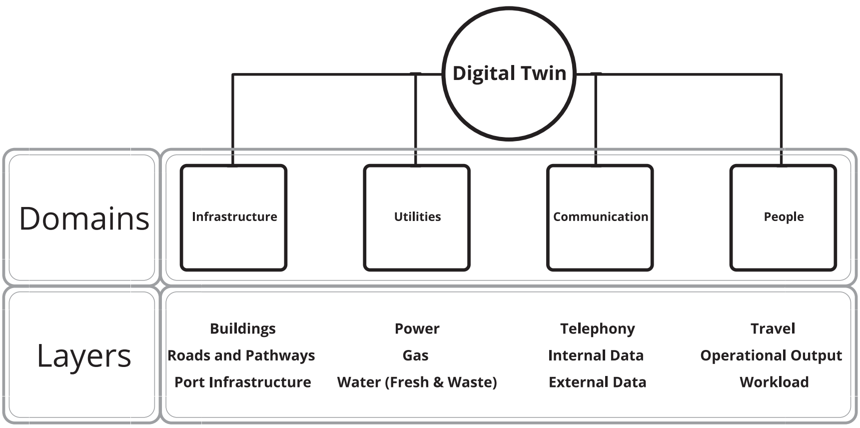
2. DIGITAL TWIN

Modern digital twin technology is being used in a wide variety of industries and for a number of different purposes. Tao *et al*. [4] and VanDerHorn and Mahadevan [5] both observed and commented on this rise of popularity, stating that digital twins were gaining interest from both academia and industry, evidenced by a notable increase in publications on and patents for digital twin technologies. The most common applications of digital twins so far have been in the manufacturing industry [6], [7] and the design and monitoring of smart cities [8], [9]. However, this concept is not limited to these two areas and can be applied in a plethora of challenges across all industries. Glaessgen and Stargel [10] discuss applications within the automotive industry, specifically for NASA and the US Air Force, to combine simulation with the vehicle's onboard computer to predict the life of the vehicles and provide additional levels of safety and reliability. Pylianidis *et al*. [11] introduce how digital twins can be applied to agriculture and Braun [12] demonstrates how digital twins can be used in medicine. Damiani *et al*. [13] show that digital twin technology has already been used in a complex maritime terminal, specifically the Port of Genoa; however, the digital twin they are discussing models the port for the purpose of supporting energy management.

Digital twin technology provides a virtual environment that simulates a real-world entity. A single digital twin contains multiple domains and layers so that when viewed holistically, the virtual entity accurately reacts just as the physical entity would. This simulation, therefore, allows the users to modify and observe data across virtualized domains and then visualize the effects. It is essential to realize that any dockyard digital twin user in this study may vary from highly technical contractors, civil servants, or service personnel looking to identify and plan the future of the site to non-technical assistants who could be MOD apprentices or junior service personnel with no technical knowledge of the site, computing, or engineering. These challenges mean that it is vital for any proposed digital twin to be visually understandable for any potential user while also providing enough valuable information to aid technical users in their planning. This suggests that any solution will need to understand both the context or environment and the users' needs to provide both the right level or type of detail and the right amount of those details.

To model HMNB Devonport using a digital twin, the authors propose using four separate domains, each with three layers. This is shown in Figure 1.

FIGURE 1: DOMAINS AND LAYERS OF THE DIGITAL TWIN



A. Infrastructure

HMNB Devonport is a large maritime site with over 650 buildings covering more than 650 acres of land [14]. The buildings layer would replicate the physical layout of buildings within the site and would then present an overlay for other layers to give additional information. Buildings will be replicated to scale, accurately showing size and shape to represent the site visually. Additionally, the buildings layer would include data regarding the use of the building for application within other layers. This layer would be the basis of the user interface, as the user would visualize the other layers around a well-known map of the site, which would immediately make the software more intuitive.

Another layer based on the physical infrastructure of the site is the roads and pathways. This layer would be vital for monitoring movements on the base and highlighting additional problems associated with a road being closed due to maintenance or an unplanned closure due to an act of God. This layer would not only show where the roads and pathways are but also the direction of travel and capacity for certain vehicles. This would then allow routing applications to run to monitor efficiency. This layer would identify single points of failure, showing routes that would not be able to occur if one road or path became unavailable or blocked. This would inform future developments to avoid single points of failure as a simple blockage could have a time-consuming and expensive effect on the site, which would be detrimental to two of the base's three priorities.

The site also has operational infrastructure, such as the dockyard basins, wharves, and docks, as well as locations where operational equipment (e.g., cranes, forklifts, and other dockyard equipment) is stored. By having these locations as a layer in the digital twin, routing can take place to see where physical assets must come from and go. This would facilitate the measurement of carbon emissions for different transfer scenarios as well as storage optimization across dockyard infrastructure, showing where equipment should be stored or where the work should take place. This could also go a step further to identify where ships and boats should be moored based on the work required to make the process more efficient. Because of the level of detail across these layers, it is then possible to approach a challenge with multiple objectives and optimize to any set of any number of objectives (see Section 3). Meeting multiple objectives through planning may involve dockyard plant and assets being transported less. This would minimize emissions, onsite traffic and congestion and save time, as equipment would not need to be moved around the site before commencing work. Workers would not need to be paid to move the equipment, and the equipment would not be unavailable for use elsewhere. This reduction in time would also reduce the overall financial impact of the work, as workers would be required to spend less time on the project.

B. Utilities

Power is required all over HMNB Devonport for almost all operations. As shown in Figure 1, the communications layers are entirely reliant on power. Without power, all communications layers would cease to function. The infrastructure layer would also be somewhat affected – roads and pathways would still be available; however, signalling and access (e.g., gates, electronic door access) may be negatively affected. This could result in people being locked in or out of buildings or areas if they are designed to fail closed or could present a security risk if they are designed to fail open. Affecting offices and workplaces, therefore, also influences the people layer. It is vital that planned and unplanned power outages are monitored so that the site can predict what would be affected. The digital twin would do this inherently – with a power layer, when an outage is simulated, the twin would be able to identify where systems are affected. For example, a power outage from the utility domain would affect certain buildings from the infrastructure domain. This could then prevent a network switch from the communications domain from functioning, which in turn could mean that the internal data layer (communications domain) would become unavailable for a portion of the site. That information would be passed to the buildings layer (infrastructure domain), showing where the network would not be available and then identifying which operations cannot take place; alternatively it would allow for planning to mitigate the risk or plan to move operations around so that the highest priority operations can take place.

Similar to mains power around the site, the gas mains would be visible on the gas utility layer for the digital twin, and this would indicate which buildings are connected to the gas mains. If there was a problem somewhere in the network, the digital twin would identify which areas would experience a disruption to the gas supply. This would highlight where vulnerabilities could be expected within the network and if an operation required gas, an alternative source could be planned.

Finally, for utilities in this particular study, water would be shown on the digital twin in its own layers, including clearwater, greywater and blackwater [15]. Clearwater is used all over the site for domestic purposes, such as drinking water or making tea or coffee in the restrooms and cleaning facilities. Clearwater must be safe for consumption and should be free from common bacteria such as legionella, which can be ensured by the correct storage of water and routine monitoring. In addition to this, clearwater is also vital for safety, as HMNB Devonport is a nuclear site and the decommissioned nuclear submarines require a constant supply of power and water to avoid overheating [16]. Considering the potentially severe consequences if power and water are not available at the dockyard, a dockyard like this is likely to benefit from a multiple-objective optimizer, as it will ensure, for example, lowering emissions without compromising safety.

These layers would also consider the source of the utility to be able to monitor effects outside of the dockyard. Any external water, gas or power supply would be integrated into the digital twin as well as onsite supplies, such as power generators.

C. Communication

The copper telephony network on site is vital for communications. Many people have migrated over to Voice over Internet Protocol (VoIP) telephony. However, many still require the copper network, and due to the age of this network, failures are not uncommon. This layer will show the distribution of copper cabling throughout the site to identify single points of failures that could cause outages over the site. This layer would also aid with planning for new cabling to be installed in the most effective way to improve efficient routing and to link with other infrastructure and works taking place.

In addition to the copper telephony network, the site has a variety of internal data networks which are air-gapped and provide local access to specific devices. Due to security, these networks must be completely isolated from each other and, in many cases, will go to the same buildings as different access permissions may be necessary for the same location. As a military site, security is of paramount significance, and any action must be compliant with the MOD's extensive security policies. The digital twin would also be able to compare existing networks and future planning within these security policies to ensure compliance and highlight any potential security vulnerabilities. Having these networks mapped onto separate layers would again make it possible to identify single points of failure. With the constant development of the site, it would also make it possible to plan future networks to be most efficient using the current infrastructure. This would allow for possible connections in any building, rather than the 'as required' request process the site currently has, as that consistently requires additional works to take place as operations move between buildings. When this is not centrally coordinated, this modular approach means that the site is regularly being worked on; however, the pit and duct network could be designed most optimally once and then installed in one action to avoid this problem.

The external network would also be a layer in the communications domain of the digital twin. If there was an issue externally that might reduce access to certain parts of our internal network, having the external connection mapped accurately would allow the site to predict problems based on external issues such as power outages.

D. People

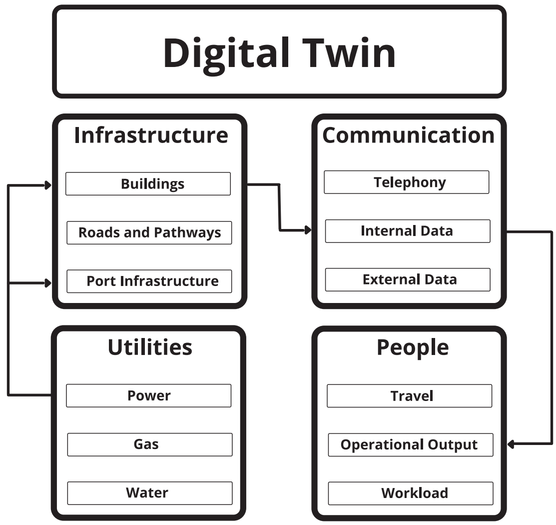
The site's workforce is made up of thousands of personnel, with thousands of additional visitors each month onsite [17]. Without these people, the dockyard would not be operational. It is unclear whether other dockyards face similar circumstances, but only a portion of the employees at HMNB Devonport live in Plymouth, the city the dockyard resides in. The remainder commute in, so it is vital to consider how staff complete their commute. The travel layer will be associated with employees to show how road traffic and public transport delays or cancellations would affect the operational output of the site. A flexible digital twin would be able to model this accurately for this research and adapt to other dockyards or new situations if the pattern of workers changes over time. Today, many people may have other options for commuting, but some may not be able to attend work if there are unavoidable delays or cancellations. This aspect of the people layer will monitor the possible effects of worker subsets who may not be able to commute to the areas in which they work. Some employees may be able to work remotely; however, personal abodes will initially be outside the scope of this digital twin at this point.

The site could also be broken into several operational outputs. Teams, workers, and buildings would then be associated with these outputs so that people can be monitored in a way that allows the digital twin to identify what outputs may be reduced due to certain people not having access to the site or not having access to a utility or network in their building due to an outage. This would then be a factor that the digital twin model would produce to identify the severity of an outage, judging by how outputs would be affected.

E. Interconnected Layers and Domains

For the digital twin to be an effective tool, layers and domains will need to share data. Figure 2 shows a simulation of a power outage – the power layer in the utilities domain would show the outage, and that would be linked with the buildings layer within the infrastructure domain, so the buildings layer could identify which buildings have lost power due to the outage. From here, the other domains would access information from the buildings layer to monitor the effect on any other layers. For example, the internal data layer within the communications domain contains active networking equipment that requires power distributed throughout the site; if this power were to be removed, then some of the surrounding buildings from the infrastructure domain would lose power, and any active communications equipment would shut down, which would result in reduced connectivity for those working in those buildings, and also for those working elsewhere but requiring network traffic through that location. Additional layers would also be required outside of the domains to define the relationships between the domains and their layers. In Figure 2, this is represented by the external directed connectors between the domains. Processes within the digital twin would then allow for interlocking communication between domains, which would render a more accurate model of the characteristics of the dockyard.

FIGURE 2: SHARING DATA BETWEEN LAYERS AND DOMAINS



3. MULTI-OBJECTIVE OPTIMIZATION

Optimization algorithms allow users to solve problems in the most efficient way. An optimization problem includes a pre-defined model, which computes inputs to simulate a real-world problem and produce an output [18]. This outcome can then be compared with the previous outcomes, and the algorithm can try again. With a single objective, the algorithm will iterate for a significant number of inputs and then present one solution that creates the most favourable outcome.

Multi-objective problems are problems that require optimization for more than one objective; the technique above is not possible when there is more than a single objective. At HMNB Devonport, three main objectives have been identified: (1) minimize financial cost, (2) reduce time and maximize efficiency, and (3) reduce carbon emissions and improve sustainability. Additionally, pre-existing goals like physical safety and policy compliance are still around and would also need to be achieved within any possible solution.

A. HMNB Priorities

Financial cost is a crucial factor in the decision-making process for almost any operation, commercial and government alike. In general, budgets are provided for each project and compromises are needed to meet the budget. Multi-objective optimization could only show solutions below a specific cost or present a variety of solutions that compromise on the three objectives but take all three into account. The efficiency of HMNB Devonport is vital for supporting the RN. The role of the dockyard is to ensure that a given number of ships are serviceable for war, should the order be given. If the time that a ship is unserviceable can be reduced, this would allow the ship to return to sea sooner, meaning that more ships would be 'ready' should the need arise. On projects where time is a factor, deadlines can be provided to the model, so only solutions that take a certain time are shown, or the best compromises could be shown, showing the most efficient solutions while taking cost and emissions into account. Sustainability is a big issue for governments and organizations around the world; the UK Government has declared that it intends to aim for a 78% reduction in carbon emissions by 2035 [1]. Plymouth City Council and ICE UK Ltd [19] report that HMNB Devonport is the largest energy consumer in the area and potentially in the whole of Plymouth. This shows that HMNB Devonport has a long way to go to reduce carbon emissions and that this needs to be a significantly weighted objective when it comes to any projects taking place. Environmental impact can be measured through the simulation, and solutions with the lowest impact that are also optimized for cost and time will be presented to the decision-maker.

With the three HMNB objectives presented above, one of the challenges is how divergent the solutions can be. In other words, completely optimizing one of these objectives (e.g., emissions) would likely be sub-optimal for the others (e.g., time and cost). Therefore, for the multi-objective problem presented here, all tasks are likely to have some compromises, which would create a set of solutions that would be balanced across each objective [20]. That said, this is highly dependent on the tasks and solutions available. Some decisions may require more compromise than others, and if people are aware of the compromises being made, they may create solutions that help satisfy multiple objectives more easily. For example, while the infrastructure for supply power may not change in the dockyard, the availability of renewable energy elsewhere could make decisions optimizing cost, emissions, and constant supply easier. All this information would then allow an informed decision based on their weighted priorities, while the solutions would have already taken the other priorities into account.

In order to combine digital twin technology and machine learning around multi-objective optimization, the following subsections discuss the most likely candidates for learning algorithms. These will be able to take a digital twin as input with its accurate representations and a set of weighted objectives defined by several different users. The output of this would then be a set of solutions to meet those objectives, complete with compromises, which the user can use, referring to the digital twin when needed, to make a well-informed decision.

B. Optimal Solutions

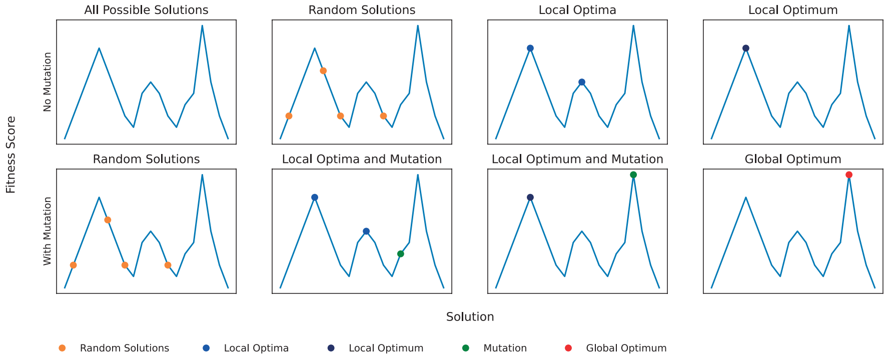
In Section 2, the authors showed how the complexity of a site, such as a dockyard, cannot operate effectively if only optimizing one goal. Moreover, contemporary issues (e.g., carbon emissions) on top of pre-existing challenges, such as fleet readiness, make decision-making even more challenging. This calls for machine learning and artificial intelligence to narrow all possible solutions to a smaller set of viable optimized solutions.

This set of balanced solutions across a number of objectives is called the Pareto optimal set, with each solution called a Pareto optimal solution [20]. Pareto optimal trade-off [21] can then occur where improvements can be made to optimize an objective further, and then at least one other objective must become less optimized. This would then allow the decision-maker to deviate from the solution deemed as the best compromise to meet the needs of the task for them, unlike other methods of multi-objective optimization. The Pareto approach treats the objectives separately; other methods use a weighted approach to prioritize the objectives into a single new objective, which can then be individually optimized for that weighting [22]. The Pareto approach, on the other hand, ensures that appropriate weighting is given to each objective to prevent decision-makers from routinely abandoning priorities for the site, which would prevent the site from, for example, meeting Government carbon emission targets [1], [2].

C. Evolutionary Algorithms for MOPs

As mentioned previously, a digital twin must evolve as the reality it simulates evolves. Evolutionary computing is based on the principles of natural evolution [18]. Evolutionary algorithms can be used to optimize multi-objective problems by starting with a random set of solutions. The chances are that these solutions would not contain the most optimized solution. The algorithm would run the solutions through the model to determine how optimized each solution would be. The algorithm would then create a new set by merging the best of the previous set to see if that has a positive effect. It is at this stage that mutations would also take place. Mutations throw new data into the set, which would allow the algorithm to explore more areas than defined within the initial random set of solutions. A local optimum would exist where moving in any direction would make the result worse. However, there may be others where the optimum is better than the original local optimum. When running an optimization algorithm, it would be possible for the initial set of solutions to not be near the actual global optimum – the most optimum of all the local optimums – if this were to happen without mutations taking place, it would not be possible to find the optimum. Figure 3 – created by the authors to demonstrate the purpose of mutation within evolutionary optimization algorithms – visualizes this. The initial set of solutions is shown by the squares, and over time they all localize on the perceived optimum, which is the local optimum on the left. The global optimum on the right is only identified in the lower example, which included mutation, allowing the algorithm to spread out further after the initial random set is created to find the global optimum.

FIGURE 3: EVOLUTIONARY OPTIMIZATION WITH AND WITHOUT MUTATIONS: LOCAL AND GLOBAL OPTIMUMS



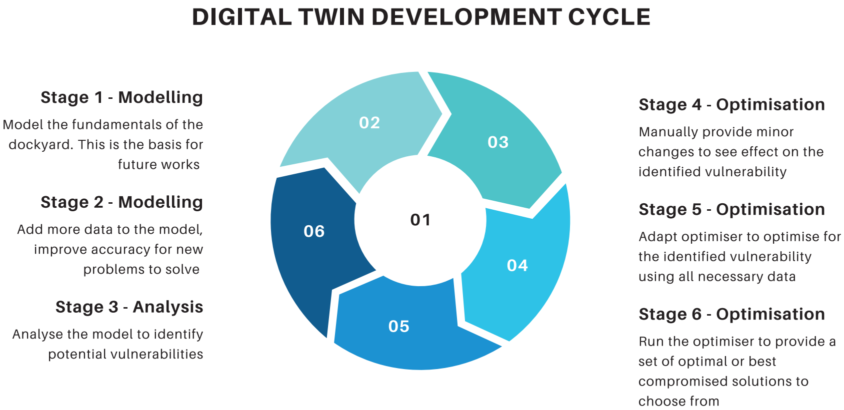
The airport gate assignment problem is a complex multi-objective optimization problem [23]; this problem is complex due to the ever-changing nature of an airport. This optimization requires dynamic optimization because live data is required to be able to produce the most optimal solutions, and as the data is frequently changing, the solutions will have to adapt. Changing solutions will also be part of the objectives, as the objectives are to maximize the airport's operational efficiency and convenience for passengers, which are two objectives that would not go hand in hand. This problem could be solved within a digital twin, which could be set up to take live data into account and then constantly run multi-objective optimization algorithms to find the Pareto optimal solutions. Through using a digital twin, a system would be created which would visualize the airport, planes and passengers while also being able to take routing and delays into account. Kaliszewski *et al*. [24] also discussed how multi-objective optimization using evolutionary computing could successfully optimize solutions using live data in the example of the airport gate assignment problem.

4. CONCLUSION AND FUTURE WORKS

A bespoke digital twin would allow the accurate simulation and modelling of HMNB Devonport as a complex site and would allow for in-depth visualization to facilitate access to the platform for any user, regardless of their technical expertise. The analysis of the digital twin would allow the user to identify potential vulnerabilities within the site and would also aid in planning future projects and minimizing vulnerabilities.

The next step for this research is to develop a prototype digital twin to act as a proof of concept for the dockyard. This will be in three distinct phases as shown in Figure 4 – (stages 1 and 2) modelling, (stage 3) analysis and (stages 4, 5 and 6) optimization. First, the digital twin must be designed to accurately model the site. Second, the digital twin will then analyse the model to identify any vulnerabilities, such as single or double points of failure. Finally, the digital twin will be adapted to use multi-objective optimization to find solutions for MOPs within the base, both those identified by the digital twin and externally inputted problems to be solved.

FIGURE 4: DIGITAL TWIN DEVELOPMENT CYCLE



This proof of concept will be compiled from gathered data, allowing for manual interaction with the data and for real-world users to keep the digital twin up-to-date. However, this could be improved for end-users by implementing a live data collection system utilizing Internet-of-Things (IoT) technology during the compilation of the digital twin model, which would both increase the accuracy of the model and efficiency, as end-users would not be required to manually interact with the raw data. Over time, this proof of concept will expand and tackle more and more problems, which will produce an estimation of the scale of the savings to be made – financial savings, environmental savings and increased efficiency – all while remaining compliant with policy and meeting the specific goals of the problem or potential vulnerability.

The level of detail in each layer could be increased so the digital twin could provide solutions to more MOPs. The number of MOPs that could be solved is almost limitless, so there will always be room for development in this regard. The digital twin could be expanded to model, analyse, and optimize other complex maritime sites, such as other naval bases (HMNB Faslane, HMNB Portsmouth) or even commercial ports. The technology also has potential uses for optimization in other industries, such as hospitals or schools, which would use data and operations differently but would still use the analysis to identify vulnerabilities and optimization to reduce spending and improve efficiency.

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