

## Container terminal operations simulator (CTOS) – Simulating the impact of extreme weather events on port operation

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This paper develops a methodology to design a Container Terminal Operation Simulation (CTOS), which simulates the vulnerability of port operations to extreme weather events. In CTOS, an agent based model was built for a container terminal at the Port of Sydney to simulate the operations of port operational assets such as cranes, straddle carriers and trucks to observe the individual and collective behaviour under various extreme weather events using a set of Key Performance Indicators (e.g. crane rates, straddle productivity, truck queue length, yard utilisation).

The CTOS results show that the crane throughput loss due to six hours of heavy rain and six hours of high speed wind (separately) is 13 per cent within a 24 hour period. While high speed wind and heavy rain have the highest impact on the crane throughput, high speed wind and flooding in the port area leads to a backlog in servicing trucks.

Using a single terminal for the purpose of the simulation, as opposed to the entire Sydney Port, is a limitation. However, the CTOS is designed and coded in a manner that permits its modification such that it can be applied to other port contexts. CTOS offers a versatile tool for port authority to enable estimating performance implications of extreme weather-related disruptions to port operations. CTOS provides an effective proof of concept prototype where the system architecture can be reused in developing an open generic port operations model.

**Keywords:** Port operations, extreme weather events, climate change, port performance, agent based simulation.

### 1. Introduction

The growing importance of port-centric logistics within increasing global concerns about climate change strengthens the case for explicit consideration of climate risk mitigation. This also necessitates the development of adaptation strategies to reduce the likely impact of climate

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change on port operations, thus enhancing port resilience to associated risks in the future. Within a logistics chain, seaports are functional nodes of significant strategic importance. They are considered as critical gateways linking local and national supply chains to global markets. However, ports are increasingly exposed to the temperamental vagaries of weather phenomena due to their coastal location and exposure to open seas. For many coastal ports it is likely that the compounded effects of mean sea level rise, high tides and increased storm surges will be the most significant risks of climate change (Wright, 2007). As such, they need to be adequately adaptive and able to effectively anticipate and avoid, or sufficiently absorb, the projected impacts of climate change, in particular extreme weather events.

Extreme weather events are unusual, severe or unseasonal weather conditions, which are at the margin of extremes of the complete range of weather experienced in the past (IPCC, 2007). These include, but are not limited to, events like cyclones, flooding, storm surge, tsunami or heat-waves. Recent examples of these extreme weather events are Hurricane Katrina in the USA, Bangkok flooding and the Japanese Tsunami, which all severely disrupted shipping movements, material handling operations, and loading and uploading of containers or freight into and out of ports. Other impacts included disruptions to essential infrastructure such as electricity and water, as well as long-lasting perturbations of global commodity supply chains.

Australia has a long history of coping with the uncertainty of extreme weather conditions. Throughout its history, Australia has experienced continuous extreme weather events such as drought, bushfires, cyclones and floods. For example, the 2009 heatwave in Melbourne, flooding in Brisbane and cyclone Yasi in Gladstone have all resulted in major disruptions to port operations. In 2007, tropical cyclones severely damaged key logistics infrastructure and disrupted port operations at Port Hedland in Western Australia. The estimated insurance cost of tropical cyclone George was \$8 million (EMA, 2007). Huge productivity losses were incurred due to work stoppages at the Port of Melbourne as a result of heat-waves in 2009. These impacts are especially important in the logistics context as they often result in costly business disruptions of a global scale because of the criticality of the role of modern ports.

Modern seaports are regarded as highly critical functional nodes linking national supply chains to global markets (Chhetri et al., 2015). Mangan and Lalwani (2008) discuss the emergence of "port-centric logistics" hubs such as Dubai, Singapore and Rotterdam. These port-centric hubs are large spatial accumulations of logistics-related value adding activities, including storage and warehousing, packing and unpacking, freight consolidation, pre-processing activities, and assembly. Arguably, modern seaports are functional nodes of value adding activities, which coordinate the seamless flow of freight through regional and international commodity supply chain networks. In addition, modern seaports are not only important as trade gateways but, equally significantly, business catalysts and central drivers of employment and growth propulsion.

Owing to the significance of import and export freight trans-shipment for goods and raw materials in the Australian economy, and the increasing global concerns about climate change and its impacts, it was considered important to undertake a study of port operational assets to assess their vulnerability to climate change-related extreme weather events.

Thus the overarching aim of this paper is to estimate the potential productivity implications of arising extreme weather situations so as to inform resilience and adaptive measures. A single container terminal within Port Botany in Sydney was used to develop the simulation. The Port of Sydney is Australia's second largest container port and typical of container terminal operations on the eastern Australian seaboard (BITRE, 2012). Sydney is also one of 136 port cities studied for extreme weather events (Nicholls et al. 2007) where it rated 19 in the top 20 for susceptibility to wind damage. Although this simulation is based on a single container terminal, the outcome is such that it can be adapted to other container terminals within Australia as well as internationally with similar operational settings. Thus, although simulating the impact of extreme weather

events on a larger port region was outside the scope of this research, the findings may be inferred broadly.

This paper presents the methodology used to design and develop the Container Terminal Operation Simulation (referred as CTOS). The paper discusses the significance of CTOS with regard to estimating potential productivity loss due to disruptions under extreme weather conditions. The research process therefore involved designing an intra-port workflow system to simulate the vulnerability of port operations to future climate change scenarios and associated extreme weather events. The simulation outcomes allow an analysis of the container handling processes within the terminal, that in turn help to address the following three research questions:

- What is the likely impact of a range of extreme weather events on the total number of containers handled at a container terminal over a 24 hour period?
- What is the average productivity loss of different operational assets under different climate change scenarios?
- What is the likely impact on the performance of key operations such as crane rate and truck queue lengths given projected growth in container numbers and the likely future climatic events?

The paper is structured as follows. Section 2 examines the linkages between seaports and climate change, followed by a description of agent based CTOS modelling approach in Section 3. The design and system concepts of CTOS are presented in Section 4, which develops a detailed description of the system concepts, port configuration and the simulation windows and outputs. Section 5 presents the climate impact assessment methodology as an input to CTOS and is followed by a discussion of key results and findings in Section 6. The paper concludes with a summary of the findings and an outline of the limitations of the methodology presented, along with suggestions for future research.

## 2. Literature review

The importance of seaports has grown significantly in recent decades with economic globalisation and the expansion of international trade. This growth in international seaborne trade has driven great expansion and innovation in ports, in terms of location, operations facilities and processes and their technologies and expertise. Furthermore, as global supply chains have become more complex, ports have become focal points of industrial clustering so that their overall significance has been greatly enhanced (Madani, 1999; Chhetri et al., 2014). The emergence and growth to prominence of Global Terminal Operators (e.g. DP World, Hutchison Port Holdings) who dominate container operations has also meant that individual ports are intricately interlinked in terms of their ownership and operations (Slack and Frémont, 2005). Arguably, seaports are becoming critical functional hubs as well as organisers of global supply chain networks. Disruption at any one of these interconnected and interdependent nodes, particularly the major hubs, would have major knock-on effects along entire supply chains (Becker et al. 2013, Lewis, Erara and White, 2006). Furthermore, because of their critical role as national and/or regional gateways, failure of operations, for any reasons, would have severe economic implications for the country or region. It is for this reason that their operational resilience and the ability to adapt to climate change are important considerations for international trade.

Evidence of recent global supply chain disruptions, following extreme weather related destruction of port facilities, can be seen in the aftermath of Hurricane Katrina and the Japanese Tsunami. In the latter case, the global supply chains for essential manufacturing components from Japan, e.g., semiconductors, electronic parts, batteries and transmissions for electrical vehicles, as well as finished products, were heavily disrupted due to the destruction of key ports

(Olson, 2012). Considering that Japan produces 20 per cent of the world's semiconductors, the economic loss for key electronic manufacturers was substantial (Amadeo, 2012). This economic loss can be directly attributed to climate driven weather events. Esteban et al., (2009) for example, modelled the economic losses related to extreme weather events by simulating the intensity and future occurrences of tropical cyclones in Japan. Hurricane Katrina's destruction of New Orleans's ports (including the port of New Orleans and the port of South Louisiana) caused major large-scale and long-lasting disruptions of commodity supply chains. Similarly Hurricane Sandy resulted in the shutting down of New York's container port for over a week with estimated damages costs of \$50 Billion (Becker et al. 2013).

As noted earlier, the exposed location of port assets makes them highly vulnerable to the impacts of climate change and extreme weather events such as sea-level rise, flooding, storm surge and strong winds. Recent predictions indicate sea level rises of 0.6m to 2m by 2100, and a doubling in the occurrence of category 4 and 5 hurricanes in the same period (Becker et al. 2011). This means that extreme weather events are likely to become prevalent at many world port locations, which in turn amplifies the need for greater resilience and adaptive capacity.

In this respect, Becker et al. (2011) surveyed 342 port authorities globally to assess their understanding of climate change and their preparedness to adapt to changing environmental conditions. They found uniformity in the response with most agreeing on the need to have infrastructures in place by the end of the century to meet changed climate conditions and concluded that "the world port community is very concerned with impacts of climate change" (p. 2). Sea-level rises did not register as a major immediate concern, largely because capital planning for ports is typically for periods of up to 10 years, much less than timeframes for predicted sea-level changes. However, other aspects of climate change featured as significant sources of anxiety. More immediate concerns were the meteorological instabilities of storm frequencies and intensities (IPCC, 2007; Nicholls et al. 2007; Ramstorf, 2007). Extreme precipitation was also highlighted as a cause of flooding, transportation interruptions and bottlenecks in the local logistics networks. They highlighted Hurricane Katrina as one event which caused economic and environmental damage of over \$1.7 Billion to New Orleans, which after five years still operates at only 80% of the pre-Katrina event (Becker et al. 2011). In recent decades 130 ports have recorded severe impacts of tropical cyclones on their port logistics operations and infrastructure. This level of threat, considering the importance of port facilities, calls for improved means of estimating actual performance and productivity impacts of process disruptions.

Modern door-to-door and just-in-time supply chains are predicated on a seamless and uninterrupted flow of container cargo. Accurate estimations of productivity loss would benefit not only port operators but also other key port users such as shipping lines, overland transport providers, and freight forwarders. As noted by Mokhtari et al. (2012), the key problem faced by port operators is a lack of appropriate methodologies and evaluation techniques necessary for analysing and modelling uncertainties at an operational level. Recent studies (e.g. Adamko and Klima, 2008; Esteban, Webersik and Shibayama, 2009; Preston and Kozan, 2001; Parola and Sciomachen, 2004; Soriguera et al. 2006; Guenther et al. 2006; Angeloudis and Bell, 2010; Lau and Zhao, 2008) suggest a range of approaches to either optimise or simulate the performance of port logistics networks and operations under uncertainties. Esteban, Webersik and Shibayama (2009) for example, used Monte Carlo simulation to model the impact of future tropical cyclones in Japan. Similarly, Esteban et al., (2012) applied their modelling to assess the port downtime damage in Vietnam due to extreme weather events, namely the potential increase in cyclone intensity and subsequent damage. Adamko and Klima (2008) used simulation to evaluate the efficiency of processes in complex systems. In designing intermodal terminals they concluded that modelling and simulation play a vital role in providing an optimal solution. Preston and Kozan (2001) analysed the major factors that influence lower throughput time for container transfer efficiency through a genetic algorithm that simulates the effects of handling equipment, different numbers of containers, terminal layout, storage capabilities and policy directives. They

found that transfer time is highly dependent on the number of yard machines and their operating heights. Parola and Sciomachen (2004) used discrete event simulation models to study the future growth of container flows in Italian ports.

Simulation is also used for container handling equipment allocation and scheduling. In this regard, Soriguera et al. (2006) investigated the internal transport subsystem at container terminals and managed to optimise the internal transport cycle. The simulation showed that dividing storage yards into import and export areas increased efficiency. Guenther et al.'s (2006) simulation found that the efficient use of transportation equipment determines the performance of the entire terminal. For example, operating dual-load AGVs instead of single-load ones can improve the AGVs performance considerably. Similarly, Angeloudis and Bell (2010) developed an algorithm based on heuristics to simulate port environments and to investigate AGV job assignments under various conditions of uncertainty.

Scheduling all the container handling equipment in a container terminal is a very complicated process. Therefore, to reach the optimal utilisation of terminal subsystems, the subsystems should be treated as an integrated unit. Solving the problems of each subsystem individually simply shifts the bottleneck to another. Lau and Zhao (2008) developed a mixed-integer programming model for this purpose and found that simply increasing the number of AGVs may not improve the terminal efficiency. Jiang et al. (2012) in similar studies found that dynamic scheduling and a container yard storage strategy increased terminal efficiency by about 8%.

Agent based simulations have been previously used in modelling container port terminal operations. Henesey et al., (2006) discussed a tool called SimPort, which is an agent based simulator for evaluating operational policies in the trans-shipment of containers in a container terminal. It simulates the behaviour of various entities in a container terminal and predicts the likely impact of various operational policies. Vidal and Nathan (2010) adopted an agent based model for comparing different configurations of container yard layout and allocation of equipment such as gantry cranes. Their simulation measures efficiency related KPI's such as truck waiting times. While these approaches are relevant for our work, with respect to the use of agent based modelling, they differ with regard to the problem being simulated and the approach taken. Our work examines the impact of extreme weather events on port operations, specifically on the equipment used at the various stages of the workflow of loading and unloading containers.

Based on the evidence presented above, CTOS-based operations impact assessment was considered highly appropriate as an approach to estimate the potential productivity loss due to occurrence of extreme weather events. It was built using an agent-based model, which is a type of computational model where individuals or agents are described as unique and autonomous entities. These entities usually interact with each other and their environment locally, leading to emergent patterns of behaviour that can be observed (Railsback and Grimm, 2011). Hence, agent based modelling allows individual actors/nodes within a process to be independently encoded with operational rules while observing the collective behaviour. While agent based models are useful in building various applications in the broader field of multi-agent systems and agent-oriented software engineering, in this work its application is to simulate a system (i.e. Agent Based Simulation). Multi-agent systems for modelling port operations however, are not new. Henesey, Notteboom and Davidsson (2003) for example, used an agent-based simulation to study the sustainability of ports and container terminals. Nonetheless, the adoption of the agent based simulation approach to mimic the behavioural port operational systems is valuable for two main reasons.

- Firstly, it enables capturing the complexity of the operational environment of a port, which includes a multitude of variables related to climate data (e.g. high temperature, wind speed, heavy rainfall) and port configuration (e.g. containers loaded/unloaded, number of straddles used, truck arrivals). Hence an ABM is a preferred choice to model possible scenarios that can occur in the operational environment by varying the values of

the multitude of variables. This would provide better understanding of the possible impact of weather related events of varying severity on the port's container operations.

- Secondly, ABM provides disaggregate level simulation at an asset level. Climate change or extreme weather events have variegated impacts on different parts of port operation. ABM allows interdependencies of different parts of the logistics systems to be measured. To illustrate, the likely impact of a reduction in crane capacity on space utilisation at the yard, can be determined. ABM provides a simulation capability to mimic the impact of different scenarios on an hourly basis at an equipment level.

### 3. CTOS - System Overview

The "Container Terminal Operation Simulator" (CTOS) is an agent based simulation of container flow at sea-land and land operations at a seaport. CTOS simulates the functions of operational assets such as cranes, straddle carriers and trucks to observe the individual and collective performance under various weather conditions. The outcomes of this simulation is a set of Key Performance Indicators (KPIs) that allow a comparison of the operational performance of assets (e.g. crane rates, straddle productivity, truck queue length, yard utilisation) under various climate change scenarios. The simulation enables a systematic assessment of different 'what if' scenarios associated with extreme weather events that are of most concern to port operations. In the following sections, we provide an introduction to agent based modelling (ABM), why ABM was selected for building CTOS, CTOS design details, simulation results and analysis.

#### 3.1 Agent Based Modelling

An Agent Based Model is a type of a computational model where individuals or agents are described as unique and autonomous entities that usually interact with each other and their environment leading to emergent behaviour (Henesey, Notteboom, and Davidsson, 2003; Railsback and Grimm, 2011). Hence agent based modelling allows individual actors/nodes within a process to be independently encoded with operational rules while observing the collective behaviour. In CTOS, an agent based model is used to simulate the operations of port operational assets such as cranes, straddle carriers and trucks to observe the individual and collective performance under various weather conditions of varying extremity. CTOS is developed using the JACK Agent Oriented Programming (AOP) language, which is a Belief-Desire-Intention (BDI) based agent platform developed by Agent Oriented Software (AOS) Pty Ltd, Melbourne. JACK is a leading agent programming platform developed as an extension to the mainstream Java programming language.

The BDI (Belief-Desire-Intention) model is a popular reasoning model for rational agents where "beliefs" represent the information about the internal and external 'environmental state' of the agent, "desires" represent the world states that the agent wants to reach, and "intentions" represent those desires that the agent has committed to pursuing (Rao and Georgeff, 1992; Winikoff et al. 2002). Intentions are also seen as partial or complete plans used to achieve adopted desires. Therefore a BDI model based agent is defined as having: a set of events or goals it can handle; a set of plans to achieve the goals; and beliefs or data about the real world/environment. The typical reasoning cycle used by a BDI agent is shown in Figure 1. In response to an event or goal "e" received from the environment or internally generated (e.g. the goal "move container" given to a crane agent), the agent selects from its plan base a set of plans ( $P_1 - P_n$ ) relevant for handling e. Based on the context conditions of the selected plans, the agent determines an applicable set of plans ( $P_j - P_r$ ) that could be used to handle the event e. A context condition defines the state of the external environment or agent's internal state for the given plan to be applicable. For example in the case of the crane, there can be multiple plans to handle a move container based on the prevailing weather, type of container etc. From the applicable set, the agent selects a single plan ( $P_i$ ) based on a predefined algorithm, which is normally specific to the

given BDI implementation. The agent then executes the actions contained within the selected plan  $P_i$  (shown in the figure as a, e, b). Actions typically found in agent systems results in interactions with the environment, raising new goals/events or reading/changing agent's own beliefs.

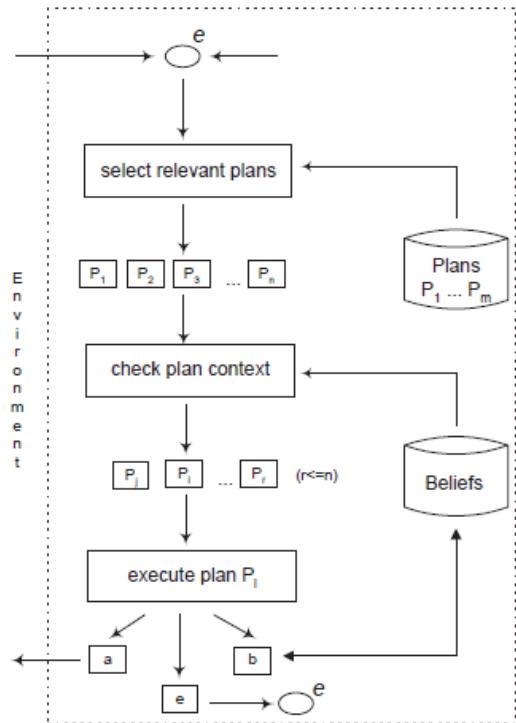


Figure 1. Reasoning cycle used by a BDI agent

The advantage of using an agent model for CTOS is in its ability to localise the operational rules of different agents in the system, which makes it simpler to build complex models with many operational assets compared to modelling the system as a whole. The visual representation of entities in the ABM helped us in communicating with non-technical stakeholders who were able to easily relate to the different operational assets in the visual simulation compared to, for example, a purely mathematical approach. They were able to engage actively in improving the simulation as their operational understanding of the port could be easily mapped to the simulation.

CTOS was developed on the container operations at Port of Sydney and simulates the sea-land and land side container movement operations of a single terminal. A single terminal was used for the purpose of the simulation, as opposed to the entire port, so that a finer scale of detail can be captured and modelled hence producing a closer to real-life outcome of possible climate impacts. The simulation system consists of three main components (Figure 2):

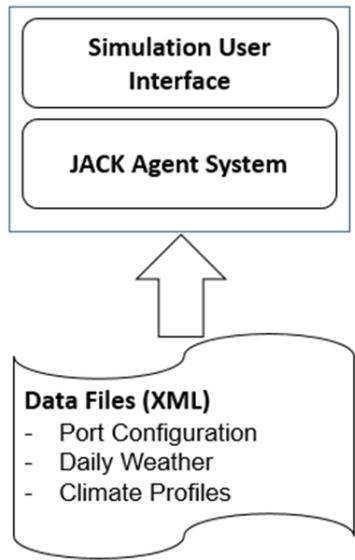


Figure 2. Simulation system components

JACK agent system: Implements the agent types and interactions in using the JACK agent language.

Input data files: The agent system requires three input XML files in order for the simulation to run. These include:

Port configuration defines the port set up with number of operational assets in use (such as cranes, straddle carriers etc), and their assignments (such as how many cranes are assigned to a vessel) and performance levels (such as number of containers handled per hour).

Climate profile defines the weather events and their impact on the performance of different operational assets.

Daily weather is based on the climate profiles defined for each hour of the 24 hour period.

User Interface: The Java based user interface allows the user to update the input files and also run the simulation.

### 3.2 Port Configuration

Port configuration defines the port set up with a number of operational assets (such as cranes, straddle carriers). It also records assignments attached to operational assets (such as how many cranes are assigned to a vessel) and their performance levels (such as number of containers handled per hour). A high level view of the various agent types found in the system and their interactions are shown in Figure 3.

The agents in CTOS are broadly categorised as "operational agents" (Table 1), which are part of actual terminal operations; and "system agents" (Table 2), which are part of the simulated environment. The Port Configuration also defines the standard operating parameters required by CTOS to run a simulation and includes the number of different operational assets (agents) in use, their operational times and assignments. This allows the system to initialise the simulation to visually illustrate a given port set up.

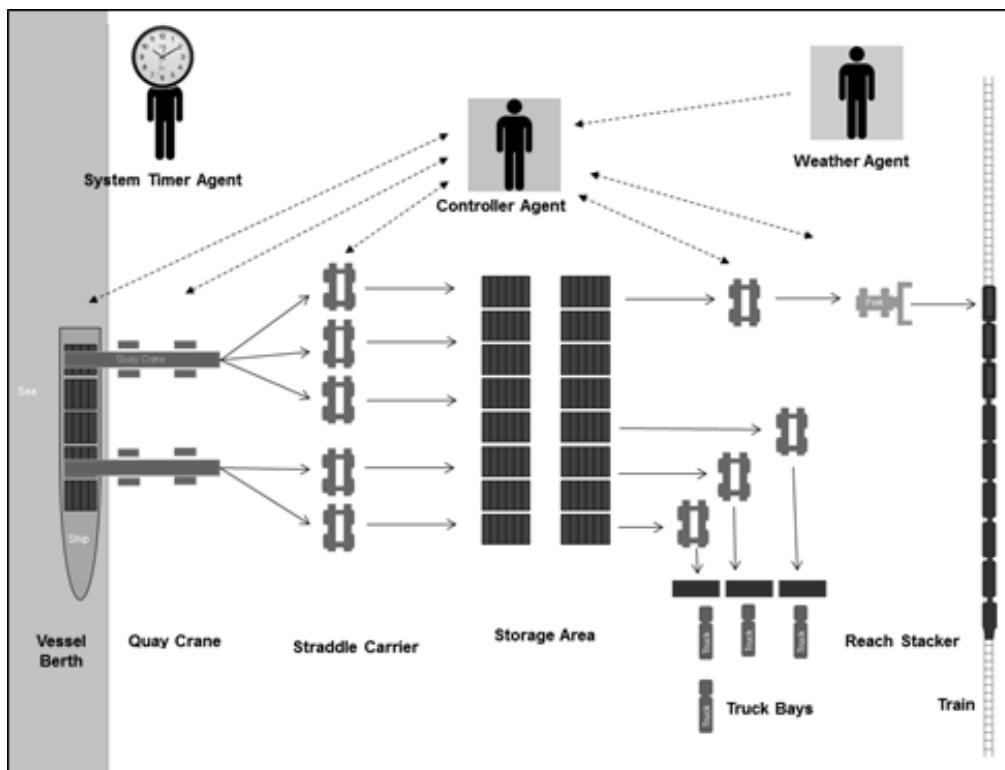


Figure 3. System agents and their interactions

**Table 1. Operational agents**

Operational Agent Type	Description
Vessel	Represents the vessels that are served at the terminal. Simulation assumes the vessel to be at the berth
Quay Crane (QC)	Quay Cranes are used to load and unload containers to/from the vessels.
Straddle Carrier (SC)	In the selected terminal straddle carriers are the main means for moving containers within the terminal area. This includes QC to yard and yard to trucks and train.
Reach Stacker (RS)	Reach Stackers are used to load/unload containers from the train
Truck	Trucks used in transporting containers
Train	Trains used in transporting containers

**Table 2. System agents**

System Agent Type	Description
Controller Agent	Acts as the central control node of the different operational agents. Responsible for initialization and communication of weather and scheduling data
Weather Agent	Generates simulated weather events (e.g. strong wind, heavy rain) of different intensities
System Timer Agent	Regulates the ticking of the system time. Each tick is representative of an hour in real time.

In the current version, the port configuration includes the following eight input parameters in the simulation:

Standard operating performance indicators for each operational asset; these include Crane rate (numbers of containers handled per hour), containers handled per hour for straddles carriers and trucks served per hour

- Number of vessels at berth
- Number of cranes assigned to each vessel
- Number of straddle carriers assigned to each crane
- Number of containers to be loaded and unloaded to or from each vessel
- Container yard capacity and current utilization
- Number of containers loaded/unloaded from trains and
- Number of containers loaded/unloaded from trucks

### 3.3 Simulation processes and outputs

The model simulates the disruption of container operations under a selected set of weather events within a 24 hour window. The 24 hour window was elected as a repeatable window of time, allowing modellers to aggregate and compute the impact for days, weeks or for months. Furthermore, the port operations are run 24/7 and a unit of one hour represents a reasonable granularity for the purpose of modelling climatic event occurrences and their impact. This allows users to assign different weather conditions to hour-blocks in a given 24 hour window, representing a chosen weather "profile" for that period. Table 3 provides an example of such a profile.

**Table 3. An example of a 24hr window weather profile**

8am	9am	10am	11am	3am	4am	5am	6am	7am
Clear	Clear	High Wind	High Wind	Clear	Clear	Clear	Heavy rain	Heavy rain

The extreme weather situations such as strong wind, heavy rainfall and heat wave, shown in the example in Table 4, are user defined weather events where the user is able to link each event to an impact on the various operational assets. Users are able to define any number of such events that they want to simulate. Table 4 shows a sample set of such weather events (under the column Impact, QC refers to Quay Crane and SC refers to Straddle Carrier).

In the current version of CTOS, the impact is defined as a productivity loss between 0 and 100% of the operational assets. However, the agents are based on the BDI model, which allows more complicated impact rules to be included as 'plans' for any future developments of the simulation. Both the hourly weather profile and the weather based productivity impact are inputs given to the system via the user interface.

**Table 4. Examples of user defined events including the impact on productivity of assets**

Event Label	Weather Event	Definition	Impact
Strong Wind	Wind	> 70km/h < 90km/h	QC = 0% productivity SC = 100% productivity Truck Rate = 100%
Heavy rainfall	Rainfall	rainfall greater than 100 mm in 24 hours	QC = 40% productivity SC = 50% productivity Truck Rate = 70%
Heat wave	Temperature	a prolonged period of abnormally hot weather	QC = 100% productivity SC = 75% productivity. Truck Rate = 50%

CTOS is able to calculate the following indicators as output to compare the performance of the terminal and the various operational agents under different weather conditions and different agent configurations such as having different number of cranes and straddle carriers assigned to move containers (Table 5). A user is able to vary the port configuration, hourly weather profiles and climate impact on each operational asset to compare the performance under each case. In this configuration a total of 3,000 containers are marked to be loaded/unloaded from three berths in a period of 24 hours, which is within the operating capabilities of the terminal we simulated.

**Table 5. Simulation output KPIs**

KPI	Description
Port Crane Throughput (PCT)	Total number of containers loaded/unloaded by all cranes in the 24hr period
Crane Rate (CR)	Number of containers handled by a crane per hour
Crane-side Straddle Hourly Rate (crane-Straddle Rate)	Number of containers handled by a straddle on the crane side
Truck Rate	Number of trucks served per hour
Total number of trucks served	Total number of trucks served within the 24hr period
Truck Queue	Number of trucks in queue after the 24hr period
Containers moved in to yard	Total number of containers moved into the yard in the 24hr period via vessels, trucks and train
Containers moved out from yard	Total number of containers moved out of the yard in the 24hr period via vessels, trucks and train

### 3.3 Climate impact assessment

In order to simulate the likely impact on the productivity of different operational assets due to future extreme weather events, we first gathered data on the future climate predictions for the New South Wales region where the Port of Sydney is located. Future climate data were sourced from the CSIRO (2007). The projections are based on a mid-emission climate scenario (A1B) for 2030, which has been developed by the International Panel on Climate Change from a 'most likely' model - (CSIRO Mk 3.0, IPCC 2000).

The projection data has been used to compare and contrast between the ports' perception of current climate threats and the future outlook. Future climate data are available for selected climate variables and extend beyond 2030. However, most ports strategise their business investment on short planning horizon of 5 to 10 years (Becker et al. 2012). The tables below (Table 6) provide a summary of the projected climate changes for 2030 in New South Wales under the CSIRO A1B climate scenario (Table 7).

**Table 6. Climate data summary for NSW, Australia**

NEW SOUTH WALES

Temperature	Most likely temperature change relative to a baseline period 1980 – 1999: An increase of annual mean temperature of $1.1^{\circ}\text{C}$ by 2030 An increase of annual mean temperature of between $1.7^{\circ}\text{C}$ – $3.4^{\circ}\text{C}$ by 2070 Consistently spring is the season that shows the greatest temperature increase
Extremely hot days	Days over $35^{\circ}\text{C}$ relative to the AWAP baseline (1974-2005) indicate a wide range; An annual increase between 4.5– 8.7 days by 2050 An annual increase between 5.9 –13.9 days by 2070
Extremely hot days (for Sydney only)	The ports temperature policy states that at 36 degrees, breaks become longer and at 38 degrees, operations related work ceases.  Current day conditions – temperatures exceed 38 degrees Celsius once annually By 2030, it is expected that the number of days to exceed 38 degrees annually will increase to 1.9
Rainfall	This projection is based on a mid-emissions scenario (A1B) for 2030 from a 'most likely' model – CSIRO Mk 3.5 (CSIRO and BoM (b), 2007) Most likely precipitation change relative to a baseline period 1980 – 1999: An annual decrease of 9.6% and 15.4% by 2030 An annual decrease between 12.7% - 24.9% by 2070 Winter and spring show the greatest decreases
Wind, storm	There is no definitive information on changes to wind speed although current work points to the likelihood of more extreme weather events, with an increase in rain intensity in spite of an overall reduction in the days it rains, and the possibility of more intense storms.
Sea level rise	The best national and international projections of sea level rise along the NSW coast are for a rise relative to 1990 mean sea levels of 40 cm by 2050 and 90 cm by 2100. These projections were released by the NSW Government in the NSW Sea Level Rise Policy Statement (New South Wales Government, 2009). Projections have been derived from projections by the Intergovernmental Panel on Climate Change (IPCC 2007) and the CSIRO (McInnes et al. 2007) and are periodically reviewed.

In addition to collecting data on climate, data on the perception of weather event thresholds of most concern to port terminals was also collated through discussions with port experts. Typical of discussions with the port experts was that some weather events triggered work slow-down or stoppage. While this data is specific to a container terminal operation, it provides additional insight into the perceived climate thresholds. Firstly, there is no formal quantity of rainfall that the port operators go by to determine whether employees should stop work. However, when work stoppage occurs due to heavy rain, it triggers all components of the workflow to stop. Cranes and straddle carriers are equipped with wind alarms. Once a wind alarm goes off, operators must cease work. Once the alarm stops, operations resume. Cranes usually stop work at 70km per hour; whilst straddles stop work at 90 km per hour. There is also a heat policy currently implemented as part of work place safety. When the temperature rises to 36 degrees Celsius, workers are required to take longer breaks. At 38 degrees Celsius, all work must cease. However, work continues as soon as the temperature drops to normal. There is an informal policy on fog. Ships are not allowed to berth if the cranes on the ship are not visible from the office building or tower. Formal or informal procedures are similarly practiced at ports to mitigate other climate related risks.

**Table 7. Climate scenarios for the simulation**

Scenario name	Description
Scenario 1	Baseline (no impact)
Scenario 2	High temperature / heatwave for six hours per day
Scenario 3	Heavy rainfall / flash flooding for six hours per day
Scenario 4	High speed wind / cyclone for six hours per day
Scenario 5	Flooding of port area affecting straddle operations for five hours

In order to calculate the likely impact, we also required productivity loss due to high temperature, rainfall and wind. These were gathered in close consultation with the Port of Sydney terminal operator. They were requested to populate the likely impact of a range of extreme weather events on efficiency levels. The performance of each asset is rated according to productivity changes that may occur during a weather event. Ratings are allocated by port representatives who are able to derive the basis of each rating from various sources including logged records, reports, personal experience or the experience of others. In the ratings, scaled from 1 to 5, 1 means 'not at all vulnerable' while 5 means 'operation ceased (operation down for weeks or more)'. The input data format for CTOS is a percentage representing productivity loss and the values we used are listed in Table 8 below.

**Table 8. Impact on selected operational assets at the container terminal**

OPERATIONAL ASSET	Impact on Efficiency (%)		
	Flash floods (rainfall)	High speed winds	Heat wave
Shore cranes	25	25	75
Straddle carrier	100	50	100
Trucks	75	75	75

Using the input in Table 8, the weather variables of rainfall, high speed winds and heat wave can have an impact on the selected operational asset efficiency. For example, the high speed wind vulnerability for a shore crane will impact on efficiency by 25 per cent.

#### 4. Simulation results

In this section we present the simulation results based on the hypothetical port configuration shown in Figure 4 and the efficiency impact listed in Table 9. While hypothetical, the port configuration reflects a case where all three berths in the terminal were used. Table 9 below shows the crane rate, crane-side straddle carrier rate and loading/unloading of trucks as performances per hour. Compared to the baseline scenario, high speed wind and heavy rain are more likely to impact on crane and straddle carrier performance. This aligns with the comments made by the port operator in our discussions where rain and wind were listed as having the most impact on container terminal operations.

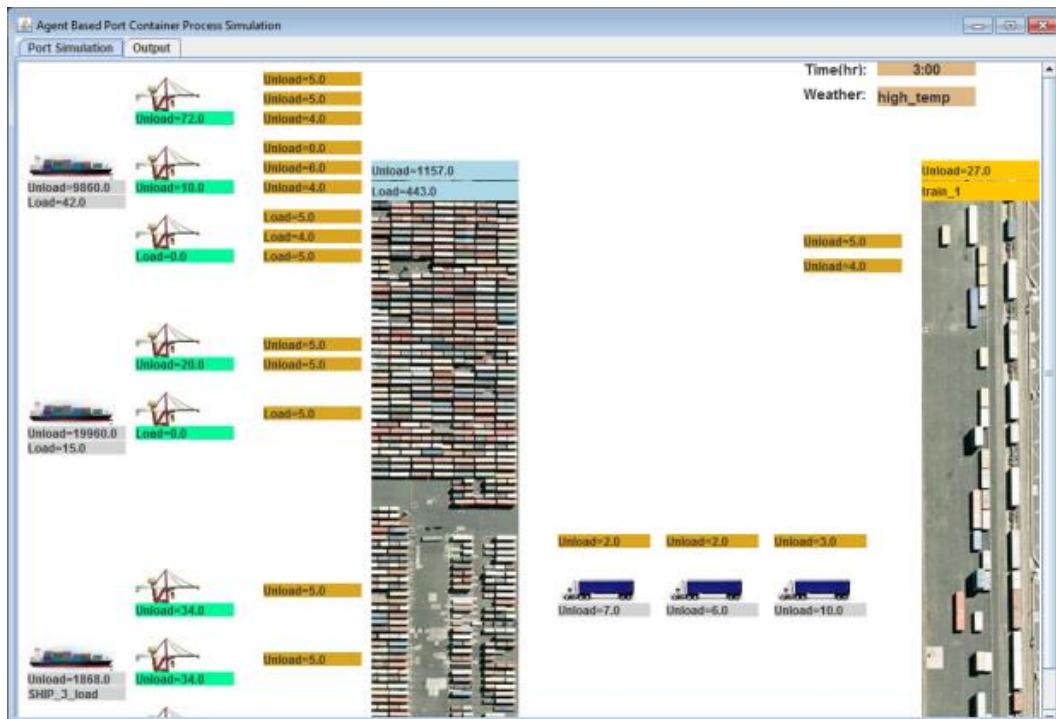


Figure 4. Hypothetical port configuration with three vessels

**Table 9. Impact on Hourly KPIs**

Scenario	Crane Rate	Crane-Straddle Rate	Truck Rate (load/unload)
Scenario 1 (baseline)	19.91	9.96	45.00
Scenario 2 (high temperature)	19.70	9.85	42.43
Scenario 3 (Heavy rain)	17.62	8.81	42.43
Scenario 4 (high speed wind)	17.62	8.81	39.86
Scenario 5 (flooding)	19.91	9.73	36.42

Table 10 shows the total number of containers (Port Crane Throughput), total number of trucks served, truck queues (backlogs) created and total number of containers moved in/out of the yard.

**Table 10. Impact on daily KPIs**

Scenario	Port Crane Throughput (PCT)	Total number of trucks served	Truck Queue	Total No. of Containers moved into Yard	Total No. of Containers moved out of Yard
Scenario 1 (baseline)	3346	945	0	3056	1635
Scenario 2 (high temperature)	3310	891	0	3008	1593
Scenario 3 (heavy rain)	2960	891	0	2658	1593
Scenario 4 (high speed wind)	2960	837	54	2646	1551
Scenario 5 (flooding)	3346	765	180	2940	1491

Table 11 shows the percentage drop in port crane throughput under each climate scenario against the baseline case. The data displayed in Table 11 shows that while high speed wind and heavy rain have the highest impact on the crane throughput, high speed wind and flooding in the port

area leads to a backlog in servicing trucks. This is mainly due to the impact of flooding and high wind on the operation of straddle carriers. The CTOS outcome for the port terminal shows that the crane throughput loss within a 24 hour period due to six hours of rain and six hours of high speed wind (separately) is 13%. While this is a considerable loss within a 24 hour period, it is important to note that port operators undertake corrective measures such as increasing their productivity in the work shifts after such an incident to compensate of productivity loss. However, this is only possible when such extreme events occur in a sporadic manner giving sufficient 'good weather' windows to make up for the time lost.

**Table 11. Impact on port crane throughput**

Scenario	Drop in PCT as a %	Drop in PCT in container numbers
Scenario 1 (baseline)	0	0
Scenario 2 (high temperature)	1.08	36
Scenario 3 (heavy rain)	13.04	386
Scenario 4 (high speed wind)	13.04	386
Scenario 5 (flooding)	0	0

As noted in Table 6, the future projections for strong wind and heavy rain show that there will be increased frequency of these weather events in the future. This may potentially result in noticeable productivity losses due to weather related disruptions. Without quantitative data on the occurrence of strong wind and heavy rain related days per year it is not possible to calculate the annual impact due to rain and high wind for the given simulation scenarios.

## 5. Limitations

With the agent approach, CTOS allowed asset level simulation, which is at a much finer granularity than a port environment-level monolithic system. Thus it allowed modellers to examine "what-if" scenarios by implementing much finer changes such as reducing the efficiency of certain asset type (e.g. straddles) or even specific assets (e.g. few selected straddles among others). There are, however, some limitations of the model which include technical aspects pertaining to scalability. The model has been designed to simulate the likely impacts or disruption to the daily container handling processes but while the process can be repeated to simulate weeks, months and years, the current implementation does not support these iterations. This means that such iterations would need to be built on top of the current tool. This is possible future work.

Following discussion with port operators, it was ascertained that it is not possible to obtain data on likely process and asset changes for the period of 2030 or beyond because port operators do not plan business that far ahead with regard to equipment and technology. Hence when simulating future scenarios, the simulation assumes status quo in currently used resources and work practices, which does not factor in the possible productivity increases due to technological advances in port equipment such as cranes and straddle carriers. Nonetheless, users can experiment with increasing the number of deployed agents and their productivity (e.g. increased crane rate to depict enhanced cranes in the future), so as to mimic increased capacity in handling containers in the future. In addition, the exclusion of container movements outside the port is another limitation, which is partly due to the lack of information on freight flow patterns based on origin-destination container flow data.

The current simulation uses a generalised impact over three categories of assets namely cranes, straddle carriers and trucks. These assets form the core operations on the sea-land and land operations of the case study terminal, providing a better estimate of impact on the port

operations. However, the simulation can be extended to model the impact on individual assets or asset groups (e.g. based on the area of the port they are deployed) rather than high level categories, resulting in finer grained analysis. A similar drill down can be performed on the scheduling of assets, which is currently static as defined at the start of the simulation by the 'port configuration'. This can be extended to dynamic scheduling where assets are re-assigned at run time, allowing users to create more detailed what-if scenarios. We also find that the efficiency loss due to weather events can be derived more accurately by analysing historical data where similar extreme weather events have impacted on port performance. In this instance, we relied on the input based on an extensive experience of few key personnel at the port terminal for ascertaining the impact percentages through vulnerability ratings.

The current model is transferable as long as the handling process remains the same with regard to the number of processing stages and associated parameter constraints. CTOS is not specifically designed to simulate the impact of weather perturbations on terminals, which handle bulk commodities such as coal or iron ore. If the workflow changes (a workflow will most likely change for a port where materials other than containers are dealt with or where machinery used differs) the simulation can be altered to accommodate for such workflow by changing the input parameters. However, these changes will need to be made in computer programming using JACK Agent Language and Java. For simplicity, the current tool was developed as a stand-alone application based on Java, which limits its use to a single user per installation. A more scalable approach would be to implement the software as a web deployable application that would permit multiple users to use the tool concurrently eliminating the need for local installations.

## 6. Conclusions

CTOS is an agent based simulation of a typical container terminal operation, implemented at the granularity of the individual operational assets in use such as quay cranes and straddle carriers. CTOS was designed to simulate a 24 hour window with hourly weather profiles. Drawing on data from a container terminal operator from the Port of Sydney, multiple simulation scenarios were computed including high temperature, heavy rain, high wind and extensive flooding impacting the port precinct over 5-6 hour duration in a single day. CTOS has an agile design structure, which is adaptive to fit to user's requirements in creating realistic 'what-if' scenarios to mimic the impact of extreme weather events on port logistics operations.

In this study, the results of the simulation showed that while the impact due to these events were non-significant on the container-related operations, rain and high speed wind made the most impact while flooding in the yard area hindering the operations of the straddle carriers led to backlog queues being created for trucks. Using annual hot days occurring at present it was possible to calculate the likely annual impact due to high temperature days. According to the simulation outcome, the current impact is a loss of 184 containers per year at present, which is less than 0.01% of the annual container trade of the port. However, it is important to note that the compounded impact of weather events occurring across a year with greater frequency and intensity within the wider port hinterland would have direct and indirect knock-on effects on port operations that were not captured in this simulation.

The significance of CTOS is that port authorities will be able to emulate the impact of extreme weather conditions, on the capacity of different operational assets, and measure the variation in performance levels and the overall throughput within the container handling process. The outputs of this simulation were a set of Key Performance Indicators (KPIs) that allowed the levels of operational performance (e.g. crane rates, straddle productivity, truck queue length, yard utilisation) and the overall throughput within the container handling process to be compared when subjected to different climate-related perturbations.

Future research will aim to customise the simulation to extend it with a “component based” approach with generic agents that can be customised by the users themselves to simulate different operational assets including links between other interacting agents. This will allow “drag-n-drop” style building of port operations simulation for any given port. Such a model will require significantly more time to design and develop, which will also include extensive requirements capturing with respect to different types of processes used in different ports. Further the climate information was specifically collected for the study terminal. Applying CTOS to different port environments will require additional research into how the climate impacts on operational processes and on assets for that terminal. The current simulation provides an effective proof of concept (POC) prototype where the system architecture can be reused in developing an open generic port operations model.

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