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THE USE OF DRY COOLERS FOR SUSTAINABLE MOULD COOLING IN MALTA

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ABSTRACT: Water and energy resources are facing significant pressures and the need for sustainable manufacturing is indispensable. This work looks into process cooling and explores the integration of sustainable cooling technologies. Playmobil Malta Ltd's mould cooling system was used as a case study and by means of a sustainability analysis, the current cooling tower/chiller system and a proposed dry cooler system were compared. Two configurations of the latter system, which differed in the order of how the cooling equipment was connected to the load, were analysed with the aim of finding the most cost effective and environmentally friendly option. The proposed dry cooler system proved to be technically and sustainably viable with one configuration achieving better results than the other.

Keywords: Sustainable Manufacturing, Mould Cooling, Dry Coolers

1 INTRODUCTION

Life on earth is facing critical times as a consequence of irresponsible actions of preceding and present generations. Climate change, fresh water shortages and fossil fuel exhaustion are some of the repercussions that are being experienced today and which will be more intense in the near future unless urgent action is taken [1, 2].

Sustainable Manufacturing (SM) has become a universal strategy to control and reduce the environmental impact in the forms of emissions and waste, while improving the economic performance and the wellbeing of those involved directly or indirectly within the manufacturing industry [3]. According to the Rio Declaration on Environment and Development, for SM to be achieved, three dimensions of sustainability have to be regarded – the environment, the economy and the social community [4].

This concept is known as the *triple bottom line* and only emerged in the last decades. Allocating importance to each of these three pillars might seem challenging, yet many organisations have proved it possible and it is being adapted in countless organisations worldwide that want to develop their activities sustainably. The mitigation of environmental impacts tackles the ecological pillar and can be achieved by boundless measures including energy and natural resources efficiency, and by applying the 6 R's (Reduce, Reuse, Recover, Redesign, Remanufacture, Recycle) to manufacturing processes [5]. The social dimension aims at enhancing the quality of life and wellbeing of both external and internal stakeholders of the organisation, and the final pillar tackles finance and aims at providing economic growth for organisations. This dimension is just as important as with any development one must ensure long-term competitiveness and economically safe developments, which in turn cultivates the continuous growth of SM [6].

1.1 Project Overview

The need to achieve a higher level of SM defines the focal point of this work. This study was done in collaboration with Playmobil Malta Ltd, a local company (one of the four European Playmobil manufacturing sites) that constantly strives to sustainably improve its manufacturing processes. The main objective was to analyse the feasibility of improving the company's mould cooling system by the introduction of a more sustainable cooling technology, with the final aim of furthering SM to a new level.

It was crucial to first understand the capabilities and limitations of both the conventional cooling technologies that are still commonly found in many systems, and sustainable cooling technologies, most of which are relatively new. Following the review on technologies, the most feasible and sustainable technology was selected for implementation in the proposed system. The existing mould cooling system at the company and the proposed setup were then analysed. The results of the analysis were then compared and evaluated, and finally led to a conclusion on the technical feasibility of the proposed technology and system, together with the environmental, social and financial improvements of implementing the project.

1.2 Industrial Cooling

Industrial cooling within the local context, which typically comprises chillers and cooling towers, was viewed differently than cooling within a global context. Malta's climate easily qualifies as a Mediterranean or subtropical climate that seems to be getting warmer in parallel with climate change, whilst relative humidity levels are generally high, particularly in winter. Moreover, fresh water is not readily available in Malta. Reverse Osmosis plants desalinate seawater and the permeate is blended with extracted groundwater. The blend is pumped for domestic and industrial use. The fresh water available in aquifers is being over extracted such that the Water Exploitation Index (WEI) was found to be on a sudden rise, where from 34.7% in 2005 it has risen to 46.5% in 2014 (a WEI greater than 20% indicates stressed water resources, while a WEI higher than 40% indicates severe water stress) [7]. These conditions can make the designing stage of cooling systems a challenging task and can limit the use of certain technology.

1.3 Conventional Technology

Reservoir cooling, chillers and cooling towers are all conventional technologies commonly found in many manufacturing sites. The latter however, can be heavily affected by climate conditions and availability of resources such as fresh water.

In cooling towers, cooling is provided by two means: sensible and latent heat transfer. Sensible heat transfer accounts for a small percentage of the cooling effect and occurs upon direct contact of air and water, as thermal energy is transferred from the water to the air. On the other hand, latent heat transfer is the major cooling element and is achieved by water evaporation. Air has the capability to hold a certain mass of water in the vapour state until it reaches a saturated state. Evaporation is therefore highly dependent on the relative humidity of air, since a higher humidity content simply means less room for water to evaporate [8].

For the evaporation process to occur, a certain amount of energy is required for water to change state from liquid to vapour. The incoming warm water supplies this energy, leading to a cooling effect by means of latent heat transfer. This explains why cooling towers cannot perform excellently when operating in climates with high levels of relative humidity, whilst also requiring large volumes of fresh water to make up for the water lost via evaporation [9].

1.4 Sustainable Technology

Some of the most sustainable cooling technologies that have been gaining popularity in the past few years are dry and adiabatic cooling, solar cooling and absorption cooling. The focus of this study though was on the first two due to Playmobil Malta Ltd's foremost interest in these technologies [10].

Dry coolers (Figure 1) have been a great response to water management issues as water use was completely abolished. This technology operates similar to an air-cooled heat exchanger that circulates a cooling fluid to transfer heat energy from the source to the sink where it is dissipated. As thermal energy is transferred to its cooling medium, the fluid is pumped into a series of finned-tubes brazed to a large number of fins to maximise the heat transfer area. Several fans propel air across the fins and tubes where heat energy is transferred to air, resulting in a cooler outgoing flow of cooling fluid. Cooling capacities of dry coolers can range from around 5 kW to more than 1000 kW; however, they are very dependent on ambient air temperatures [11].

Adiabatic coolers utilise the same working principles and have a similar structure. The only difference resides with how the incoming air is further cooled via an adiabatic process. Adiabatic panels are attached to the air inlet sides and are constantly wetted with a fresh water supply such that incoming air becomes saturated as it passes through these panels; hence the wet bulb temperature is used for cooling rather than the dry bulb temperature. When water is recirculated, ultraviolet filters are used to eliminate the risk of Legionnaires' Disease Bacteria (LDB) growth, however, in some systems water is not recirculated to eliminate the use of filters [8]. EcoMESH and Jaeggi, manufacturers of adiabatic coolers claim that water use in this technology is reduced by up to 75% when compared to cooling towers, while still providing cooling capacities up to 4000 kW [13-15].

Figure 1: A typical V-shaped dry cooler [16]

Studies on actual systems have proved the benefits that sustainable cooling technologies can bring about. In China, a comparison between coal-fired power plants cooled by wet and dry cooling systems states how well designed dry cooling systems can leave significant positive impacts. One of the highlighted impacts was water consumption, where the total consumption in a year of a particular power plant under study was reduced by 67%, a reduction of more than 8 million cubic meters per year [17]. In addition, BrightSource Energy's solar thermal power plants also uses dry cooling technology which has reduced their total water consumption by 90% and by the year 2012, 56 power plants in the United States had switched to dry cooling systems from the commonly used once-through and recirculating systems [18, 19].

4 METHODOLOGY AND CALCULATIONS

2.1 Feasibility Study

The methodology employed for this project was based on a feasibility study. Following the preliminary research, an analysis of the current mould cooling system was required to determine its technical performance and also to develop criteria for comparison with the system that was later proposed, such as the cost of cooling, water and energy consumption, Carbon Dioxide (CO_2) emissions and Global Warming Potential (GWP). The proposed cooling system was then analysed and compared to the current system. From this comparison, a conclusion could be drawn determining the feasibility of the proposed system both in terms of performance and the discussed aspects of sustainability.

To obtain a more accurate feasibility study, the analysis of both systems was conducted for summer and winter including different relative humidity levels and day and night atmospheric temperatures. Furthermore, an extreme situation with a relatively high atmospheric temperature was selected to represent a worst-case scenario for humidity and temperature dependent technology (Table 1).

Table 1: MET Office Data

Season	Temp. (Day)	Temp. (Night)	Relative Humidity
Winter	17.5°C	11.5°C	77%
Summer	28.0°C	20.5°C	70%
Summer (Extreme)	36.0°C	25.0°C	66%

The analysis covered an entire 24-hour day for each season and cooling load, separating daytime from night-time hours as the company benefits from lower electricity tariff rates during the night. Upon agreement with Playmobil Malta Ltd, a 75% cooling load was then selected to model an entire year with both seasons.

2.2 Current Mould Cooling System

The setup of the current mould cooling system (Figure 2) comprises of two main tanks, two chillers, a counterflow forced draught cooling tower and two heat exchangers for water basin (reservoir) cooling. The operation of the current cooling system (labelled as System CT) is configured in multiple stages of cooling, where each stage is responsible of operating particular cooling technologies. The higher the stage, the greater the cooling capacity of the system. The cost of cooling also varies accordingly, as energy intensive cooling is introduced in the last stages.

The need for cooling stages arises due to a varying cooling load. Although water enters and exits the moulds at fixed temperatures of 29.7°C and 31.3°C, the flow of water through the injection moulding plant can fluctuate, depending on the number of machines in operation, hence leading to a variable cooling load. The maximum cooling load (100%) was found to be 371 kW while the other loads varied proportionally. Four different cooling loads were considered for this study: 100%, 75%, 50% and 25% load depending on the water flow rate.

There are five cooling stages for the current system and another that is operated during the night to cool the warm water in the basins.

- Stage 1: Water basin (one heat exchanger)
- Stage 2: Water basin (two heat exchangers)
- Stage 3: Water basin (two heat exchangers) and cooling tower
- Stage 4: Water basin (two heat exchangers), cooling tower and one chiller
- Stage 5: Two chillers only
- Stage 5 (night cooling): Two chillers and water basin (two heat exchangers)

The night cooling stage provides cooling for both the load and the water in the water basins. The cooling capacity at this stage caters primarily for the load, while the rest of the capacity is utilised to cool down the water basin to a lower temperature.

The cooling capacity of each stage was determined in order to be able to calculate the time of operation at the selected scenarios. Each of the chillers has a cooling capacity of 342.5 kW, which was obtained from the technical data provided, while the 'cooling' provided by each heat exchanger of the water basin was assumed to be constant at 138 kW, a value that was calculated with the available data on water temperatures and flow rates.

Cooling capacities of the cooling tower were unavailable and CIBSE's Psychrometric Chart was used for the analysis of the air passing through the cooling tower [20]. Both latent and sensible heat transfer were catered for such that the difference in enthalpy of the entering and exiting air resulted in the total heat transfer. The cooling capacities (Table 2) were then found by multiplying the total heat transfer by the different air flowrates of the cooling tower.

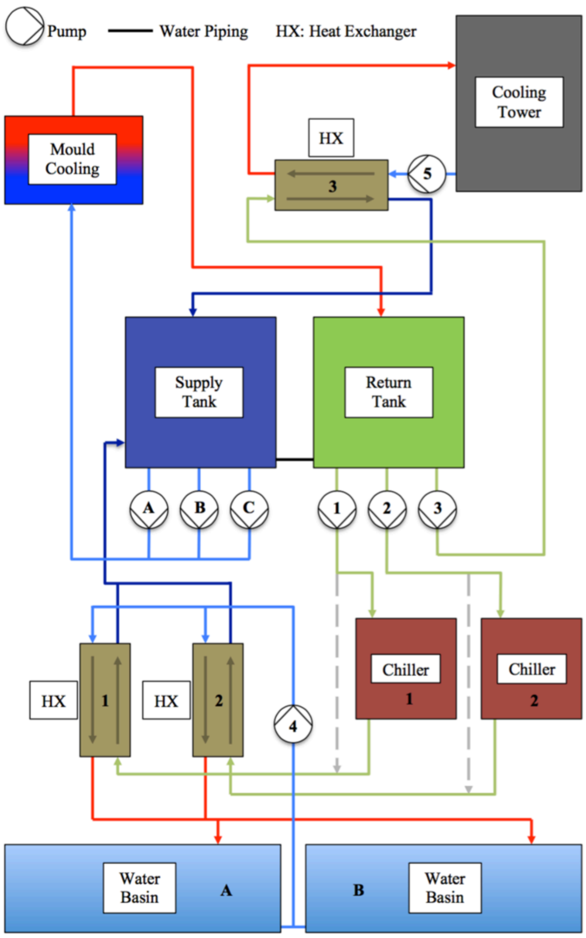


Figure 2: The setup of the current mould cooling system.

Table 2: Resultant cooling capacities of the cooling tower.

Period	Cooling capacity (kW)
Winter Night	600.7
Winter Day	547.6
Summer Night	600.7
Summer Day	560.9
Summer Night (Extreme)	641.0
Summer Day (Extreme)	240.4

The yearly maintenance costs for each cooling technology, which included consumables, replacement parts, cleaning expenses, subcontracting expenses and labour costs were provided as follows:

- Water basins 6,680 Euro
- Chillers 192 Euro
- Cooling tower 5,044 Euro

2.3 Proposed Mould Cooling System

The second part of the feasibility study started with the selection of a more sustainable technology. With water consumption as a major issue within the company, the dry cooling technology was selected with the aim of eliminating or minimising water consumption and costs as much as possible. In addition, the cooling tower was eliminated, as it is highly water intensive and the high humidity levels limit its cooling capability. Figure 3 illustrates the proposed setup incorporating a dry cooler.

The selected dry cooler had a nominal cooling capacity of 407 kW, however, it was important to assess its feasibility within local climate conditions, in particular the dry bulb temperatures in the different seasons and scenarios considered, as its performance tends to be highly temperature dependent.

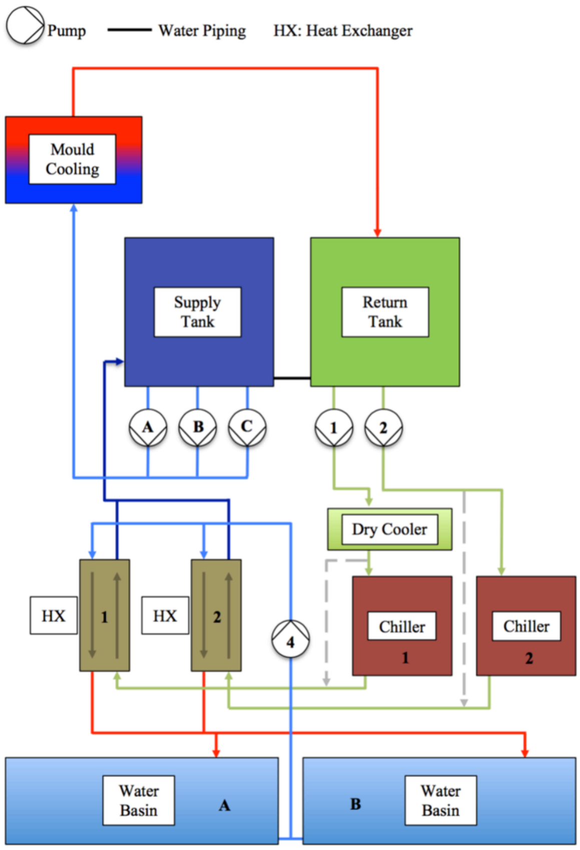


Figure 3: The setup of the proposed mould cooling system.

The cooling capacities of the dry cooler (Table 3) were found at a full air flowrate using all its six fans. The dry cooler acts similar to a crossflow heat exchanger; hence a constant effectiveness value was used for constant flow rates of both air and circulating fluid.

At night, the dry cooler was found to be highly capable of cooling, particularly in winter. However, the cooling capacity decreased substantially at higher temperatures, such that the end effect resulted to be heat gained rather than heat loss due to an air temperature higher than the fluid temperature. In such a situation, the dry cooler was switched off, due to its cooling incapability.

Table 3: Resultant cooling capacities of the dry cooler.

Period	Cooling Capacity (kW)
Winter Night	579.7
Winter Day	385.5
Summer Night	289.9
Summer Day	58.6
Summer Night (Extreme)	154.2
Summer Day (Extreme)	-185.0

With a change in setup from the current cooling system to that proposed, the configuration of equipment in the different stages of cooling was also adapted due to the introduction of the new technology and the removal of the cooling tower. Due to the dry cooler's low operating costs, a configuration that uses the dry cooler in the earlier stages of cooling was designed (labelled as System DC 1). However, since the dry cooler was found to be incapable of cooling effectively during the day in the warmer season, a second configuration was designed (labelled as System DC 2), where the dry cooler was introduced in the last stages. This would give the system the possibility to operate the dry cooler mostly when it is highly effective, while trying to avoid its use when the system is operating at the lower loads. The stages of cooling are listed below:

System DC 1

- Stage 1: Dry cooler
- Stage 2: Dry cooler and water basin (one heat exchanger)
- Stage 3: Dry cooler and water basin (two heat exchangers)
- Stage 4: Dry cooler, water basin (two heat exchangers) and one chiller
- Stage 5: Dry cooler and two chillers
- Stage 1 (night cooling): Dry cooler and water basin (two heat exchangers)
- Stage 2 (night cooling): Dry cooler, two chillers and water basin (two heat exchangers)

System DC 2

- Stage 1: Water basin (one heat exchanger)
- Stage 2: Water basin (two heat exchangers)
- Stage 3: Water basin (two heat exchangers) and the dry cooler
- Stage 4: Water basin (two heat exchangers), dry cooler and one chiller
- Stage 5: Dry cooler and two chillers
- The night cooling stages were the same as in System DC 1

The night cooling stages provided cooling for both the load (mould cooling) and the water in the water basins.

Maintenance costs for the dry cooler amounting to €240 were also provided for comparison with the total cost of maintenance of the current system. These costs covered maintenance for an entire year and mainly consisted of cleaning and general checks for fluid leaks. Maintenance costs for the water basins and chillers remained the same.

2.4 Comparison of the Cooling Systems' Performance

For each given cooling load and scenario, each cooling system was hypothetically run for a 24-hour period. From this analysis, the time of operation for each particular stage was calculated and the electricity consumption and the cost of cooling were established. Eventually, modelling an entire year on a 75% cooling load also helped determine the performance of the cooling systems on a long-term period closer to a real situation. The best performing system could then be identified by comparing these results.

2.5 Sustainability Assessment of the Project

Having successfully addressed the performance of the different systems, a sustainability assessment was then carried out. In this section, the proposed system that displayed the best performance is compared to the current cooling system. With sustainability as the main focus, the effects of the proposed system on each of the three pillars were evaluated.

Environmental assessment was carried out by calculating the reduction in CO_2 emissions and GWP, two commonly used environmental metrics. The CO_2 emission rate used was based on the emissions of the current Delimara power station [g]. In addition to this, the reduction in emissions was also calculated for the planned gas conversion of the power station. The GWP is a measure of the amount of heat that a particular gas traps in the atmosphere that can potentially contribute to global warming. CO_2 is the benchmark for all other gases when measuring GWP, such that the CO_2 equivalence factor for 1 tonne of CO_2 is equal to a GWP value of 1 [22].

Financial feasibility was then assessed in several ways. First, the simple payback period method was used to analyse the time required to gain back the money invested in the project by the revenue that it would generate. Secondly, the Net Present Value (NPV) method was used to analyse the net amount of capital generated after a period of 10 years, while taking into consideration the time-value of money. This value was finally compared to a secure bank investment in order to bring out the difference between the two types of investments.

Lastly, the social community pillar was evaluated to assess the benefits that both internal and external stakeholders would experience if the dry cooler had to be installed. This included the time for maintenance work, safety of the employees and health of the general public.

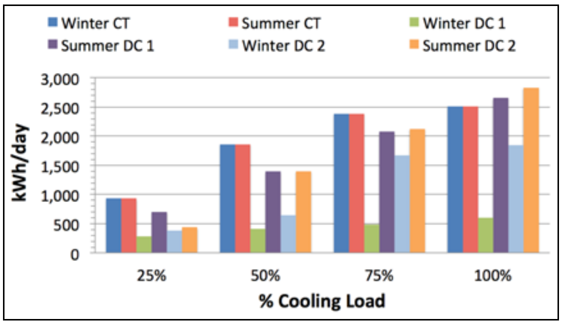
3 RESULTS AND DISCUSSION

3.1 Electricity Consumption and Costs of Cooling

The calculated energy consumption of the current system and the results obtained from an energy audit that was carried out on Playmobil Malta Ltd's cooling system at the end of 2015 were compared. The energy audit was based on the second cooling stage of the current system and was hence compared with the results of the calculated 50% load at which the second cooling stage was triggered. The difference in energy consumption between the two varied by less than 8%, instilling a good level of confidence in the approach used for this work.

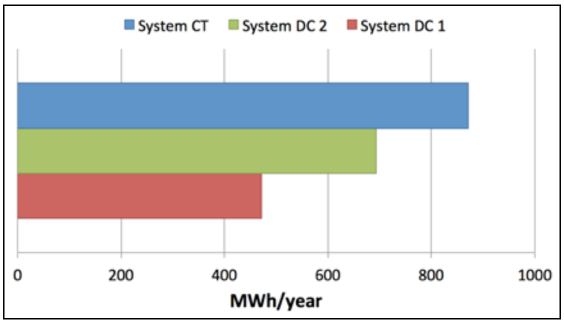
Graph 1 shows the electricity consumption for the different systems over a 24-hour period, where CT, DC 1 and DC 2 refer to System CT, System DC 1 and System DC 2 respectively. One can notice the drop in consumption during the winter season with both proposed configurations; however, System DC 1 was more effective especially at the higher loads. This was mainly the result of the dry cooler's high effectiveness during cold days and its low electricity consumption. During warm days however, the proposed system reduces consumption by a much smaller amount, and at the 100% load, consumption is even higher than that for the current system. The reason for this increase is due to the dry cooler's low effectiveness during the summer. In such a situation, the cooling tower would be a better option, as its effectiveness is higher in warmer days.

Graph 1: Daily electricity consumption of the analyses cooling systems.



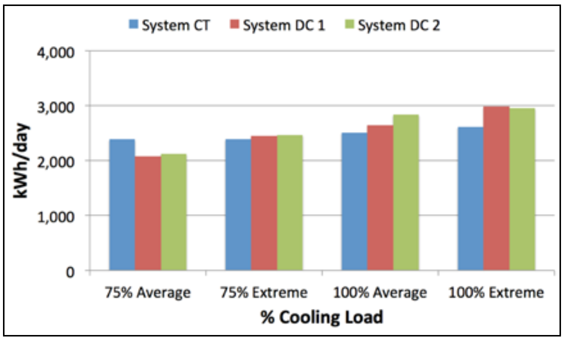
The 75% daily electricity consumption was then extended over a whole year, taking into consideration the two seasons. The results (Graph 2) show a drop of 20% between System CT and System DC 2, while a larger drop of 45% was noticed between System CT and System DC 1. The large drop in electricity consumption in winter at a 75% load (Graph 1) was the main contributor to such an extensive reduction in the yearly consumption, as it also managed to balance out the higher cost of cooling during the summer.

Graph 2: Annual electricity consumption of the analysed cooling systems at a 75% load.



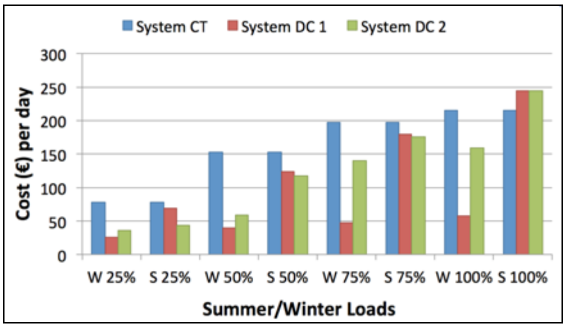
The calculations for electricity consumption were also extended for the extreme summer scenarios that were studied. In Graph 3, System CT shows the least increase in consumption, as the cooling tower was not as heavily affected as the dry cooler by the extreme situation. As shown in Table 1, the cooling tower proved to be capable of supplying more than 240 kW of cooling, whereas the dry cooler (Table 2) had to remain switched off as it was incapable of providing cooling. In fact, both of the proposed systems experienced an increase in consumption at the extreme situations.

Graph 3: Daily electricity consumption of the analysed cooling systems at the average and extreme summer temperatures for a 75% and a 100% cooling load.



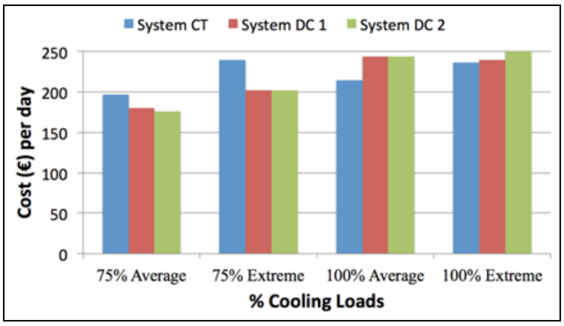
The cost of cooling was then derived from the working hours of the different stages and equipment. Due to the different day and night tariff rates, one could not simply multiply the electricity consumption by the tariff rate, but it was necessary to calculate the cost of cooling from the duration of operation of the equipment. A power factor of 0.95 was assumed for all of the equipment used. With a similar reasoning to how the daily electricity consumption was obtained, Graph 4 illustrates the differences in the cost of cooling for each system during both seasons.

Graph 4: Daily operational cost of the analysed cooling systems at the different loads for summer (S) and winter (W).



As for the electricity consumption, the cost of cooling was also calculated for the extreme situations (Graph 5). The rise in cost per day for Systems DC 1 and DC 2 is smaller than that for System CT, hence resulting in a lower financial impact when extreme situations are experienced. These changes can be explained by the differences in the night cooling stages. At high loads, the water basins are used to a maximum; hence the night cooling stage would be required for quite a prolonged amount of time. The current system utilises two chillers for cooling, which come at a relatively high cost of operation. On the other hand, both of the proposed systems utilise the cost-effective dry cooler in addition to the chillers for night cooling, therefore more cooling capacity would be available for water basin cooling, leading to a shorter period of cooling time.

Graph 5: Daily cost of operation for an average and an extreme summer scenario at a 75% and a 100% load.



3.2 Optimum System Selection

From the preceding calculations and results, all systems were capable of dealing with the different cooling loads in both seasons including the extreme situation. Nonetheless, System DC 1 displayed an outstanding performance when compared to the other two systems. Extensive reductions in both cost and consumption were obtained by System DC 1, while water consumption was completely eliminated. With the implementation of this system, maintenance costs would also be reduced drastically by around €4,800 every year as dry cooling systems do not require frequent and labour intensive maintenance or chemical dosing; only regular cleaning and periodic checks are required.

3.3 Environmental Benefits

From the sustainability assessment, it was found that the proposed system chosen as the best performing system provided multiple environmental benefits. Water consumption would be completely eliminated, leading to savings of up to 275 m^3 of fresh water every year at a total cost of around €1,100. The implementation of the proposed system would also reduce CO_2 emissions and GWP as a result of reduced electricity consumption by more than 45%, amounting to 226 tonnes of CO_2 with the current power station, and 184 tonnes with the planned power station operating on natural gas. The reduced electricity consumption of the mould cooling system would also reduce Playmobil Malta Ltd's overall factory consumption by 1.75%.

3.4 Social Community Benefits

The social pillar was not directly tackled in this study as it mainly focused on the physical system. However, the proposed system has certain potential with regards to the social community. Firstly, the internal stakeholders of the factory are less exposed to hazardous chemicals that are usually required to maintain the cooling tower. Additionally, the dry cooler requires a much smaller amount of hours of maintenance, hence making workers more available for value-added work that can contribute to increase the company's turnover, unlike maintenance work. Finally, a reduction in CO_2 emissions is also considered as a tremendous benefit for the entire Maltese population, as fewer emissions would be released in the atmosphere.

3.5 Financial Feasibility

The cost of investing in the proposed system would amount to a total of €35,500 including purchasing of the equipment and any other peripheral devices, installation and necessary testing and modifications, while the annual return that would be obtained from implementing System DC 1 would amount to €34,924. The latter resulted from the difference between operating and maintaining the current and proposed systems. The payback period resulted to be slightly more than 1 year, while the NPV after 10 years amounted to €286,576. In comparison to the considered bank investment, which only results in a final value of €43,274, it is clear that an investment in such equipment is much more feasible given that it could render a substantial amount of turnover. In conclusion, the stated amounts show that investing in the proposed system incorporating the dry cooling technology that was studied is financially viable and would lead to multiple benefits in all aspects of sustainability.

4 CONCLUSIONS

Throughout this project, the possibility of introducing a dry cooler within Playmobil Malta Ltd's mould cooling system was analysed by studying the different aspects involved including performance of the systems together with the aspects of sustainability. System DC 1, one of the configurations for the proposed setup incorporating the dry cooler was found to be the best system in terms of performance and cost of operation. The system would be capable of dealing with the foreseen cooling loads at any season, including worst-case scenarios that represent heat waves which tend to occur locally in summer.

The results of the analysis have doubtlessly harmonised with the reviewed literature, while the benefits advertised with such technology have been shown by the extensive reductions not only in cost, but also in the multiple environmental and social benefits.

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