ENGN2226 Systems Engineering Analysis

Portfolio: Leak Detection System for Parabolic Trough Solar Power Plant

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1. Abstract

Time, energy, material, cost and optimisation analyses have been conducted with a consideration of human factors on a leak detection system for Valle 1 and 2 parabolic trough power plants in Spain. Structurally, use of steel frame and lithium-ion batteries are suggested with the maximum allowed weight of 430kg. In terms of dynamics within the power plant system, 14 robotic units are suggested including 2 back-up robots to minimise the running cost and still achieve reasonable time frame from the onset of the leak to sealing off.

2. Introduction

Parabolic trough solar power plants use a set of curved mirrors called parabolic trough concentrators to focus sunlight on a receiver to generate electricity. The focused light heats up a fluid such as water, thermal oil or molten salt that runs through the receiver. The heated fluid is then used to run a conventional power cycles such as Rankine or Brayton cycles to convert the collected thermal energy to electrical energy (Lovegrove and Pye, 2012). The receivers consist of two tubes, one inside the other where the inner tube carries the heat transfer fluid (HTF) while the outer tube is evacuated to reduce the convection heat loss. Evacuation also helps prevent oxidation of the inner tube which happens at an accelerated rate at a high temperature (Price et al., 2002). One of the main issues that occurs frequently in parabolic trough solar power plants is leakages from the receivers: they have a high failure rate due to the complexity of the design. Failure rate of 4~5% per annum is expected according to Price et al. (2002) and this is equivalent to 375 leaks every year for Valle 1 and 2, or approximately one leak every day (based on total of 7500 receivers (Ibarguren et al., 2013)). Since leakage means a loss of valuable resource as well as the collected thermal energy, it is in the power plants' interests to locate the leaks as quickly as possible. Leakages can even reduce the overall efficiency of the power plant by lowering the average temperature of the collected HTF.

Ibarguren et al. (2013) reported that the leak detection system employed by Valle 1 and Valle 2 parabolic trough solar power plants in Spain, owned by Terresol Energy Investments, S.A. were highly inefficient and labour-intensive as the leak detection is currently being performed by human inspectors on a moving car using thermographic cameras. Due to the enormity of the field (it takes approximately two hours to inspect the solar field by car) and poor road conditions, this method is prone to missing a leak. In order to solve this problem, the author identified and evaluated three leak detection systems using systems engineering techniques as part of the ENGN2225 portfolio. The four-wheel robotic system with thermographic camera was concluded to be the best option for Valle 1 and 2. Figure 1 illustrates the concept of the recommended design which is based on the system constructed by Ibarguren et al. (2013). The improved detection efficiency has been confirmed experimentally by the authors under test condition; they reported that some minor leaks that were detected by the robotic system could not be identified by human inspectors. In this paper, a set of new techniques from ENGN2226 will be used to suggest some improvements on the recommended design from the previous portfolio. Valle 1 and 2 are recently built (became operational in December 2012) and thus it is very likely other existing parabolic trough solar power plants use the human inspection system. It is hoped that a successful application of a robotic leak detection system will set a good standard as an innovator and encourage adoption of the technology for other solar power plants.

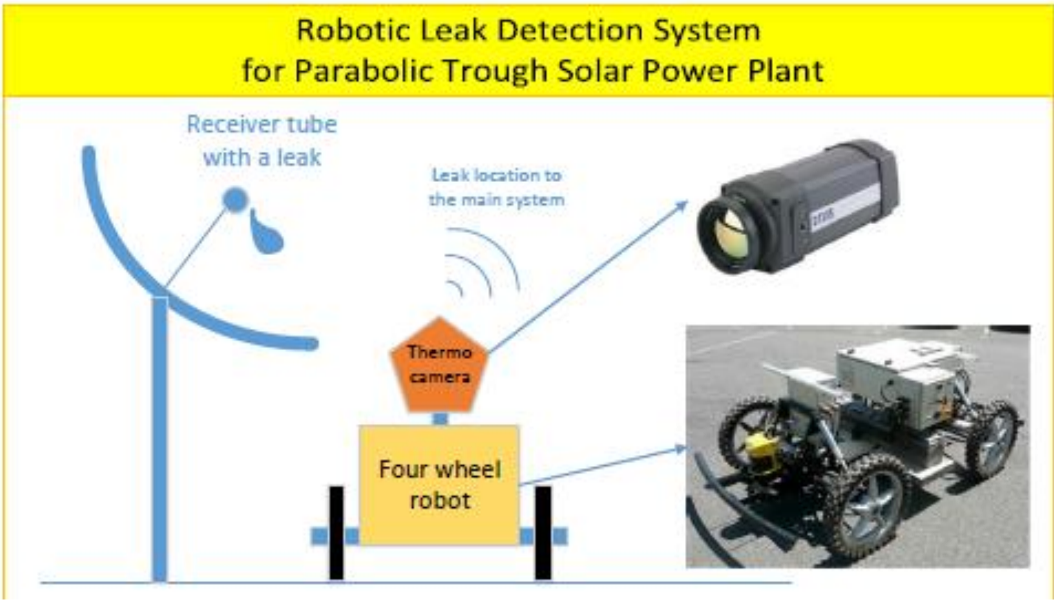


Figure 1. Recommended leak detection system from ENGN2225.

3. Summary of systems engineering analyses

From the analysis techniques learnt in ENGN2226, steel-framed robots with lithium-ion batteries have been identified as the best solution for Valle 1 and 2 solar power plants. Purchasing 14 robotic units is recommended to balance between the cost and reliability of leak detection. Following six aspects of the system were studied to arrive at these recommendations.

1) Human factors: using the anthropometric data, the maximum weight of the robotic system was found, which was 430kg. This ensures that 95% of the staff being able to push the robotic system without any external energy sources.
2) Time analysis: a PERT chart was constructed which illustrated the entire inspection process. 5 robotic systems were suggested as the minimum number required to detect leaks in 30 minutes.

3) Energy analysis: lithium-ion and lead-acid batteries were compared using Sankey diagram and lithium-ion batteries were concluded be better due to their higher efficiency.
4) Material analysis: based on the concept of embodied energy, steel was recommended for the frame of the robot. Embodied energy was higher for lithium-ion than lead-acid batteries, but lithium-ion was chosen as performance was a more important aspect than the environmental impact.
5) Cost analysis: life-cycle costs of the robotic and conventional inspection systems were calculated and it was found that the robotic system had lower ongoing cost although the initial cost was higher. Using the optimum number of robotic systems found from the optimisation part, the benefits of the robotic system was also confirmed as the payback period was very short with respect to the conventional system.
6) Optimisation: risk associated with power plant shutdown as a result of a leakage was quantified in terms of cost and minimum total cost was found to identify the optimum number of robotic systems, which was 12. 12 robots can achieve leak detection within 15 minutes and sealing off within 45 minutes from the onset of the leak. 2 more robots were suggested as back-ups.

4. Human factors

The parabolic trough concentrators focus enormous amount of heat on the receiver which is situated on the focal line of the parabolic mirrors (Lovegrove and Stein, 2012): concentration ratios between 50 and 80 suns can be reached using the parabolic trough concentrators (Price et al., 2002). Such high concentration is required to heat the HTF that is moving in the receiver to a temperature as high as possible, typically around 400˚C (Hoffschmidt et al., 2012). Hence, it is very dangerous for the staff to approach the concentrators during operation. The suggested robotic detection system will be able to provide the staff a safer workplace by eliminating direct contact with the potentially hazardous environment.

Although this system is designed to autonomously investigate the solar field for leaks, there will be some human interactions still present particularly at the start and the end of the detection process. The most likely interaction would be made through a remote controller to move the robot to and from the solar field and the storage area. However, there could be situations where it needs to be moved by human power, such as during maintenance. An anthropometric data will be utilised to calculate the maximum mass of the robot in order for staff to move it without other external power sources (e.g. electricity).

When a round object rolls, the surface material in front of the object retards the forward motion as it is being deformed (Hibbeler, 2010). For a wheeled object to continue moving, it must overcome the rolling resistance. Force due to rolling resistance is expressed by:

$$F_r = cW \tag{1}$$

where c is the coefficient of rolling resistance and W is the weight of the object. Table 1 lists three different coefficient of rolling resistance for different contact surfaces that the robot may experience. The maximum force is required if the contact surface is loose sand but this is unlikely as loose sand would not provide enough rigidness required to erect the concentrators. Since Ibarguren et al. (2013) described that the road was at least asphalted although the condition is poor, solid sand seems like a good choice for the worse case approximation. Hence, c=0.08 will be used to find the maximum weight.

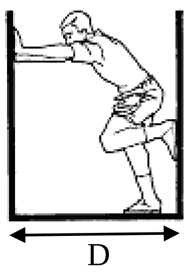
Table 1. Coefficient of rolling resistance values for different contact surfaces

	C
Car tires on tar or asphalt	0.03
Car tires on solid sand	0.04 – 0.08
Car tires on loose sand	0.2 – 0.4

To ensure that the detection system is light enough to be moved by the most of the staff, anthropometric data will be used. As the power plants are situated in Spain, it would be desirable to have data on the average push force that a Spanish person can exert but no such data was available. A compromise had to be made and the data from NASA was employed instead. This data was organised as a function of the distance from the surface of the force plate to the opposing vertical surface (wall or footrest) against which the subject brace themselves (NASA, 2008b). A number of assumptions and approximations are needed to calculate the maximum mass of the detection system, as listed below.

1) There is no direct data on push force of females but the report suggests using a data that compares female and male muscular strength. On average, total body strength of females is about 62% that of males (NASA, 2008b).
2) Average force and standard deviation values from Table 2 will be taken to represent the overall population. This will allow to take into account variations in height of the staff (variations in height changes the push conditions).

Table 2. Maximal static push force for males

	**Force-plate height (% of shoulder height)**	**Distance (marked D) (% of shoulder height)**	**Force (N)**	**Standard deviation (N)**
	50	100	774	214
	50	120	778	165
	70	120	818	138
		Average	790	123

Two standard deviations will be used as the extreme values so as to ensure that the design can cover more than 90% of the population as suggested by NASA (2008a) (2 standard deviation will cover 95%). Hence, the minimum bound is 544N for males. Using the first assumption, the minimum bound for females will be 62% of the male data which is equal to 337N or 430kg. This means that the maximum mass of 430kg will ensure that the 95% of the staff will be able to push the detection system without external energy source. The limitation of this calculation is that the data for females were obtained indirectly based on that of males'. This produces a large uncertainty in the calculation as there is no guarantee that the push force of females will follow the same trend or distribution as shown for males. As the minimum force that can be exerted is the key parameter in determining the maximum weight, the importance of the female data is even more pronounced. However, compact cars can be pushed by females usually which definitely weigh more than 430kg so this calculation seems reasonable given that the road condition was chosen as solid sand.

5. Time analysis

Queue theory is a mathematical study of waiting in line (Sherman, 2010). It is a common time analysis technique that tells useful information about the system under study when a queue forms as a part of the system. The concepts in the queue theory could be translated to fit this leak detection system, for example interpreting λ (the expected arrivals per period) as the number of inspections required per day to satisfy the safety measure set by the company and μ (the expected service completions per period) as the number of inspections a robotic system can do per day. However, it was found that this analysis did not inform any useful information as the system does not really involve any type of 'queueing'. Although the power plant will have multiple inspections scheduled every day at a specific time, these inspection events will not form a queue in the conventional sense. That is, this system is flexible such that if one inspection event is missed then it will simply not be performed or a new schedule will be created reflecting the changes.

Table 3. Estimation of times for inspection steps

Activity	**Time**	**ID**
Prepare robot	5 minutes	A
Move from base to solar field	10 minutes	B
Inspect	120 hours	C
Move from solar field to base	10 minutes	D
Prepare for next inspection	5 minutes	E
When a leak is detected during inspection		
Process the data from sensory system	30 seconds	C1
Send information to control post	30 seconds	C2

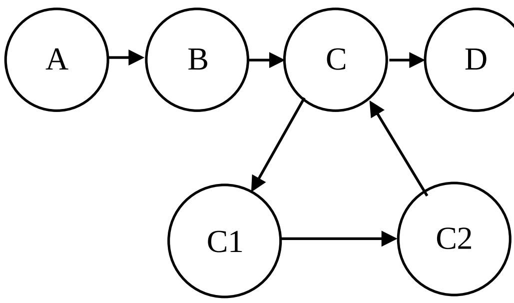


Figure 2. PERT chart of leak detection process

A progression of the detection steps are presented graphically in Figure 2 with the estimated times listed in Table 3. This is called a PERT chart which is a network planning technique, commonly used to determine a project's planned completion time (Reid and Sanders, 2009). As outlined in Ibarguren et al. (2013)'s paper, the aim of employing the robotic system is not to minimise the leak inspection time but to increase the accuracy of detection. Therefore, the inspection time for the robotic system is assumed to be 2.5 hours which includes 2 hours for the actual inspection (the same as that for human inspectors) and 0.5 hours for miscellaneous preparation steps (e.g. travelling to the solar field, setting the inspection route, etc.). The loop of C-C1-C2 is repeated as many times as there are leaks during the inspection. If there are multiple robotic units then leaks can be detected more promptly. Assuming that any leak must be detected within 30 minutes from the onset of the leak, inspections must take place at a frequency of 30 minutes to satisfy this safety measure. This indicates that five robotic systems are needed.

6. Energy analysis

An energy-mass balance audit is a diagram that illustrates how energy and mass flow in and out of the system. The energy-mass balance audit for the robotic system is provided in Figure 3 where the system boundary was chosen as the exterior of the robot. The robot is an electric vehicle and the motor was assumed to be cooled by ambient air. It was also assumed that the electricity from the battery is used to run the sensory and communication electrical systems. Weather conditions were included in the other considerations category but they will not play a major role as the power plant will not be operational anyway when there is no Sun. From this audit, a more comprehensive energy analysis can be built on using a Sankey diagram. A Sankey diagram is a diagram that represents energy flows as bands with thickness proportional to the amount of energy (Pye, 2013). Following assumptions and approximations were used to construct the Sankey diagrams for the robotic systems that use lithium-ion batteries (Figure 4) and lead-acid batteries (Figure 5).

- The actual inspection takes 2.5 hours as outlined in time analysis.
- The speed of the robot was assumed to be 20km/h. This is the speed used in testing done by Ibarguren et al. (2013). Hence, the robot travels 50km per inspection.
- The electric vehicle efficiency varies from one model to another and also depends on the road and driving conditions so it is desirable to have the specific efficiency value for the chosen robotic system. However, this information was not known and the efficiency had to be estimated. The efficiency data for the Tesla Roadster was used to perform this calculation. Eberhard and Tarpenning (2006) stated that the Roadster was 86% efficient using lithium-ion batteries and covered 2.53km/MJ (this is the distance the car can travel by each MJ of electricity from the battery, so this does not include any losses). Assuming the efficiency of 80% to take account the various conditions the robot will encounter, the robot can travel 2.53km/MJ×0.8=2.024km/MJ. This is equivalent to 0.494MJ/km or 24.7MJ per inspection, 20% of which is lost through transmission and chemical conversion processes.
- However, the robot actually uses lead-acid batteries (Robosoft, n.d.). Lead-acid batteries are less efficient than the lithium-ion batteries: it was found that only 30~50% of the rated power can be extracted from lead-acid batteries (PowerTechSystems, 2013).

Using 2.53km/MJ as the energy requirement as before with the best performance of 50% energy recovery leads to 39.5MJ per inspection.

- It is assumed that a computer is used to process information from the thermographic camera and communication system (e.g. GPS). The energy consumption of the computer also varies with the type of machine and the task to be performed. The maximum value of 250W was chosen from the work by Bray (2006) which leads to 2.25MJ per inspection.
- Thermographic camera used in the recommended system consumes 24W (FLIR, 2014), leading to 173kJ per inspection.
- Transceiver power consumption is very low. The highest value from the work by Wang and Sodini (2006) is only 37mW for 10Mbps and this adds up to 333J per inspection, which is almost negligible.

From the Sankey diagrams, it is clear that the lithium-ion battery performs much superiorly than the lead-acid battery. In both cases, the amount of energy drawn by the sensory and communication subsystems is a small fraction of the input energy, indicating that no extra batteries are required to implement the design. Another advantage of the lithium-ion batteries is that they are less sensitive to extreme temperatures than lead-acid batteries. Even at 33˚C, the performance of the lead-acid is significantly downgraded compared to lithium-ions (Albright et al., 2013). As the robots will be operating under the full Sun, lithium-ion batteries are recommended for reliable performance.

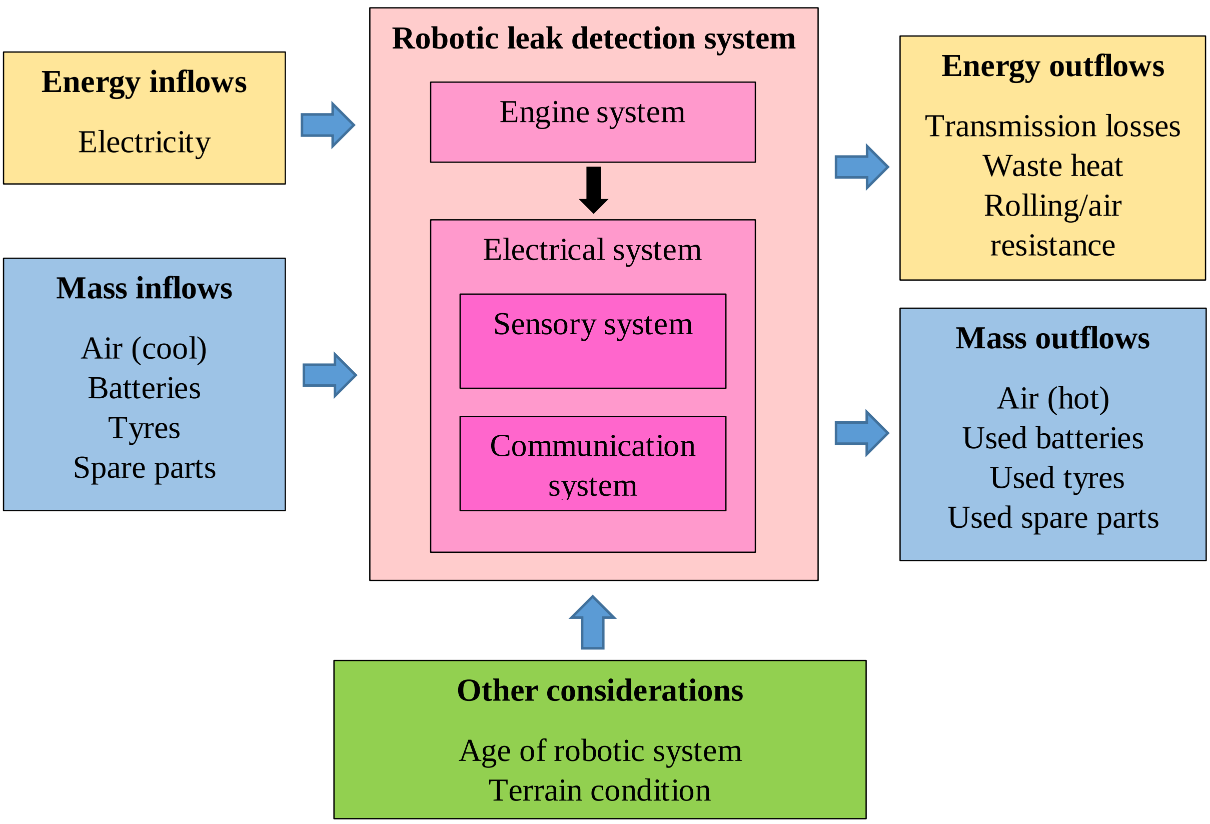


Figure 3. Energy-mass balance audit for robotic leak detection system.

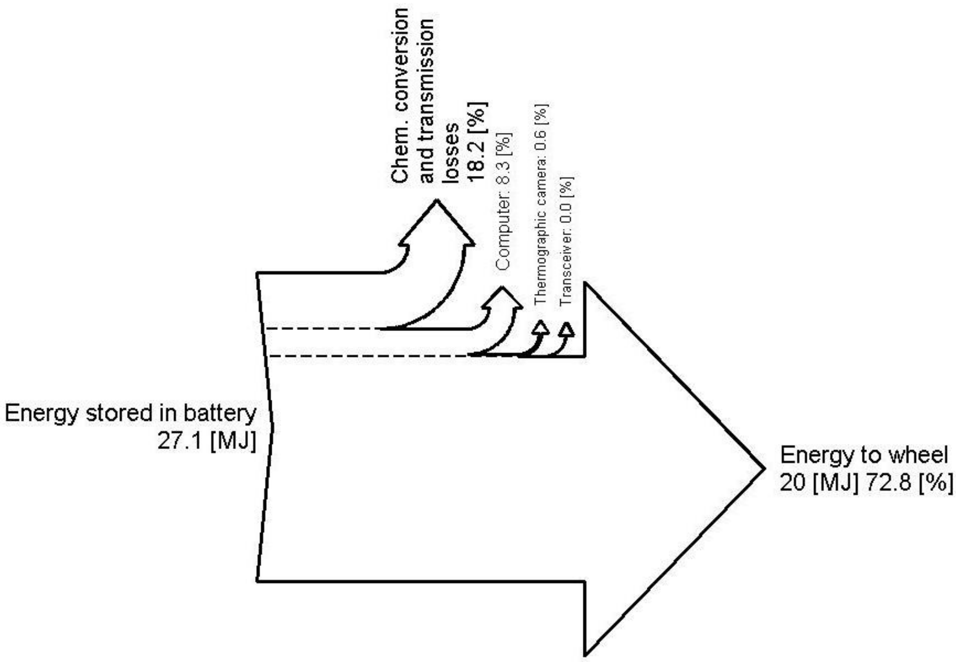


Figure 4. Sankey diagram for the robotic system with lithium-ion battery

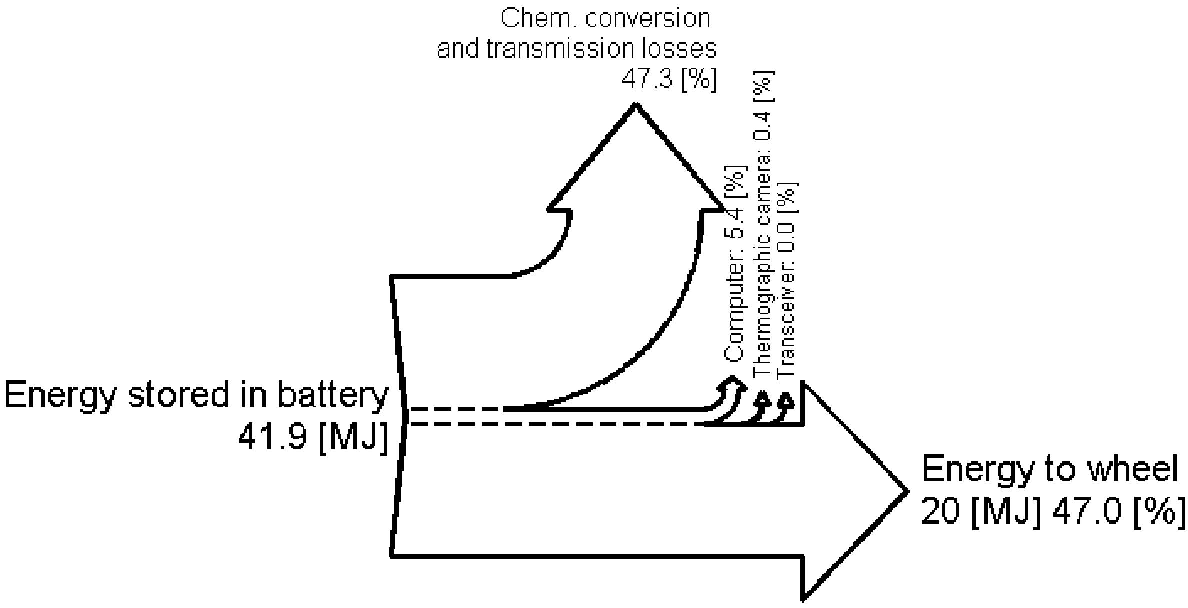


Figure 5. Sankey diagram for the robotic system with lead acid battery

7. Materials analysis

Materials analysis constitutes an important part of the Life-Cycle Assessment (LCA) which is a process that evaluates all the environmental burdens associated with a product or process over its whole life-cycle to identify opportunities for environmental improvement (Hammond and Jones, 2008). To perform the materials analysis, it is required to know construction materials of the system as well as the corresponding weight to calculate the total embodied energy. However, it was not possible to find the materials list for the four-wheel robot specifically (the electrical systems are ignored as this will be only a small fraction of the total weight), nor that of electric cars. Instead, the materials break-down for the Mercedes-Benz Class C Kompressor (petrol engine) was used as the guideline. This source was useful for this analysis as the breakdown was material-wise, not component-wise. Mercedes-Benz (n.d.) reported that the material with the highest use was steel, constituting 62.2% of the total weight of the car, followed by polymers at 18.7%. The remaining 19.1% were mainly metals and alloys which were not specified in detail. However, these values cannot be applied directly to the robotic system as no batteries were included in their analysis which constitutes a significant proportion of the total weight in electric cars. Since the battery weight for the robotic system is not known, this must be approximated based on the total weight. Westbrook (2001) indicated that a typical small electric car requires 400kg of lead-acid batteries. Assuming that the car weighs 1200kgt, this means that the batteries would constitute 33% of the total weight. From this approximation, 142kg of lead-acid batteries is required for a 430kg robot (this was the ergonomically viable maximum weight found in the human factors section). For lithium-ion batteries, only 30% of the lead-acid battery weight is required to power the same vehicle (Westbrook, 2001), which translates to 43kg. For steel and polymers, the total weights were calculated using the quoted percentages from Mercedes-Benz (n.d.) but based on the weight excluding the battery weight i.e. for steel, (430-142)kg×0.662 = 188kg is the calculated total weight. As the report does not specify the polymer types, an average value of embodied energies of polypropylene, polyurethane and PVC was used (these three are the largest plastic contributors in cars (Szeteiova, 2010)).

Based on all of these assumptions, the materials audit was conducted as shown in Table 4. The audit clearly shows that it is far better to use the lead-acid batteries than lithium-ion batteries. This is still the case considering the fact that the lithium-ion batteries operate twice as much cycles as the lead-acid batteries do (The Royal Academy of Engineering, 2010). Although the impact of lead-acid on the environment was found to be smaller than that of the lithium-ion batteries, the lithium-ions are ahead in terms of performance. It was decided that performance had higher priority than environmental impact from the perspective of the power plant owner so lithium-ion batteries is still recommended.

Table 4. Materials audit for the robotic system with two types of batteries. Specific embodied energies for steel and polymer are from Hammond and Jones (2011) and those for batteries are from Ashby (2009)

Material	Specific embodied energy (MJ/kg)	Weight (kg)	Total embodied energy (MJ)
Steel	29.36	188	5516
Polymer	25	53	1327
Batteries (Lithium-ion)	324 (99Wh/kg)	43	22032
Batteries (Lead-acid)	19 (39Wh/kg)	142	2700

The second highest impacting element in the system after lithium batteries is steel which is mainly used for the frame of the body. Aluminium and ABS are alternatives to steel but their embodied energies are much higher than that of steel (157.1MJ/kg for aluminium and 77.83MJ/kg for ABS, (Hammond and Jones, 2011)) and thus steel is a better option environmentally. However, they are much lighter than steel and it could be beneficial to replace some parts with aluminium or ABS if a significant reduction in weight can be achieved. However, without detailed knowledge of the system, it is hard to suggest any replacement and thus steel is recommended as the substance for the body.

7.1. End of life issues

Appropriate treatment of the materials after the end of life can effectively minimise the environmental impacts. Reuse must be the first option; if a specific part is causing the system to malfunction, then this part can be repaired or replaced instead of replacing the entire unit. If the damage is extensive, repair may not be possible. In such cases, recycling should be the next option. For steel, this is not a problem as it does not get downgraded through the recycling process (Planet Ark, n.d.-b). Also, both types of batteries can be recycled (Planet Ark, n.d.-a, Australian Battery Recycling Initiative, n.d.). On the other hand, not all plastics can be recycled, although the three plastics used in the analysis are all recyclable (Association, 2014, Clean up Australia, 2009). The problem with plastics is that the quality decrease as they go through the recycling process so that their recyclability is limited, indicating that robotic systems with as low plastics usage as possible are preferred. Both the end-of-life issues and embodied energy suggest that steel frame is a more environmentally viable option and hence all-steel body frame is recommended for the robotic system.

8. Cost analysis

Even though there may exist a perfect solution for a given problem, the implementation or adoption of such solution will ultimately be limited by the economic viability. A perfect solution that minimises the profit is not likely to be chosen over a not-so-perfect solution that can do a decent job and profit the business. In this section, the key components of the life-cycle cost will be evaluated for the robotic and the conventional human inspection systems. Following assumptions were used and they are summarised in Table 5.

- The cost of robotic system is typically not set by the manufacturer as they are custom made and hence the cost varies with the features required by the customer. Hence, the price for a similar car (but smaller) quoted by Mihai (2014) was chosen, which is USD 25000 or approximately EUR 19600.
- The price for the thermographic camera was hard to find as many manufacturers did not specify it on their websites. The price of a basic model listed on a technical equipment online store (TestEquipment, 2014) was chosen for this analysis, which was AUS 500, or EUR 340.
- For human inspection system, it was assumed that a small electric car was used. The Mitsubishi i-MiEV was chosen as it was one of the cheaper options at EUR17900 (Mitsubishi Motors, 2014). Two seat electric cars were cheaper but excluded as they did not have trunk.
- Maintenance cost was assumed to be EUR 2350 (Ingram, 2012) and applies to both systems as both are based on electric vehicles.

- Battery comparison between the robot and the car was hard, so the operations cost for Mitsubishi i-MiEV was used for both systems. The car consumes 30 kWh/100 miles which is equivalent to EUR 0.9/inspection (one inspection is 50km) with the price of 9.6 Eurocent/kWh in Spain (European Commission, 2014). Assuming 4 inspections per day and operation of 365 days produces EUR 1314 every year.
- Average salary of EUR 32000 per year was assumed for staff which is the average salary for mechanical engineers in Spain (PayScale, 2014).
- For human inspection system, one unit consists of an electric car, one thermographic camera and two staff.
- Resale values at the end of life were ignored.
- It was assumed that at least three staff are needed for the robotic system: one at the control centre and the other two for dealing with the leaks in the solar field. Each of the mechanics was assigned a car, so two cars were added in the robotic system.

Based on this information, plots were generated for the initial and ongoing costs as a function of the number of units, as shown in Figure 6. The plots show that the initial cost is higher for the robotic unit but the ongoing cost is much lower. However, since the total number of required units is not known yet, total cost comparison will be done based on the result from the optimisation section.

Table 5. Life cycle cost comparison

	Robotic system		**Human inspection**
Purchase cost (hardware and software, including a thermographic camera)	EUR 19940	Purchase cost (an electric car for inspection and a thermographic camera)	EUR 18240
Operations (mainly charging the batteries)	EUR 1314/yr	Operations (mainly charging the batteries)	EUR 1314/yr
Maintenance (regular services)	EUR 2350/yr	Maintenance (regular services)	EUR 2350/yr
Major repairs	N/A	Major repairs	N/A
Disposal	N/A	Resale	N/A
Number of robots required	Variable	Number of cars and thermographic cameras required	Variable
Number of staff required	3	Number of staff required	Variable
Number of cars required	2	Number of extra cars required	0

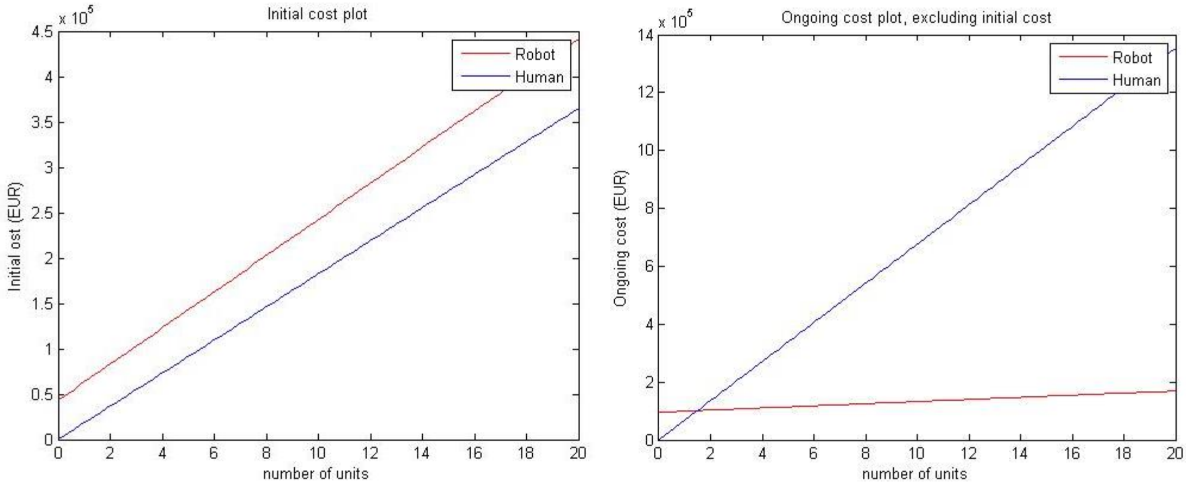


Figure 6. Initial and ongoing cost comparisons for robotic and human inspection systems.

9. Optimisation and reliability

Optimisation is the process of adjusting the inputs characteristics of a device, mathematical process, or experiment to find the minimum or maximum output or result (Haupt and Haupt, 2004). In this section, the optimal number of robots will be identified by balancing the cost and the safety requirements. In the time analysis section, it was found that minimum of 5 robots were needed to detect leaks within 30 minutes. However, deploying the robots at 30 minute frequency cannot meet the safety measure as the robots are merely detection units and cannot perform repair tasks. A more realistic scheme can be set by considering the time the staff will need to get to the leak and seal off the leak. The estimated times for this is presented in Table 6 which sums up to 30 minutes. From this result, it can be concluded that the amending the leak within 30 minutes is almost impossible unless the robot passes by the leak which has just started. To reliably deal with leaks under 30 minutes, a continuous detection is required, which is not practical.

Table 6. Estimated times for steps from receiving the leak alert from the robot to the actual seal-off

Activity	Time	ID
Assign mechanics	5 minutes	F
Get to the leak	10 minutes	G
Seal off the leak	15 minutes	H
Total	30 minutes	

In order to compare the cost and safety to find the optimal number of robots, both quantities must be expressed in terms of the same metrics. For this analysis, safety was converted to cost. However, this was not a trivial exercise as safety is not a quantitative variable and the documentation of the types of risks associated with undetected leaks and the resulting cost was hard to find. Instead, a mathematical approach was use to approximate this. The assumptions are listed below.

- It was assumed that a major leak occurs only once a year and it takes one month to repair.
- Valle 1 and 2 generate 350000MWh per annum (NREL, 2012) and one month of shutdown brings the total loss of EUR 2,800,000 based on 9.6 Eurocent/kWh (European Commission, 2014).
- It was assumed that the risk of shutdown, as well as the loss exponentially decayed as the number of detection units increased. Hence, $L(n) = L_0\exp(-an)$ was used where L is the loss in EUR, L_0 is the maximum loss, a is the exponential constant and n is the number of units per inspection. L_0 is taken to be EUR 2,800,000 with an assumption that zero detection will lead to 100% shutdown. To calculate a, it was assumed that the risk of shutdown becomes negligible when there are 30 rounds of detection per 2.5 hours (i.e. detection takes place every 5 minutes). Rearranging the exponential loss equation, a is approximately -0.5 and the equation becomes: $L(n) = 2{,}800{,}000*\exp(-0.5n)$.

L(n) and the ongoing cost for robotic system are plotted in Figure 7 and the minimum is found at n=12. Therefore, it is concluded that the power plant is expected to maximise the profit when 12 robots are employed. This will ensure that any leak will be identified within 13 minutes and fixed within 43 minutes from the onset of the leakage. Two extra robots is suggested as back-ups. From the payback plot in Figure 8, it can be seen that the benefit of the robotic system is substantial, even including two back-up robots; payback period is less than 0.1 year or about 1 month. Hence, this validates that the robotic system is a better detection system for the power plants.

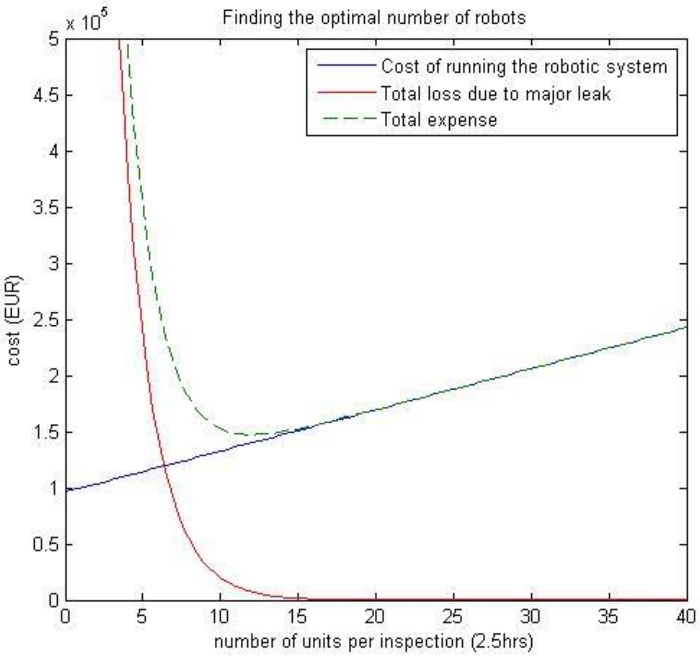


Figure 7. Plots of the loss associated with shutdown and the ongoing cost for robotic system

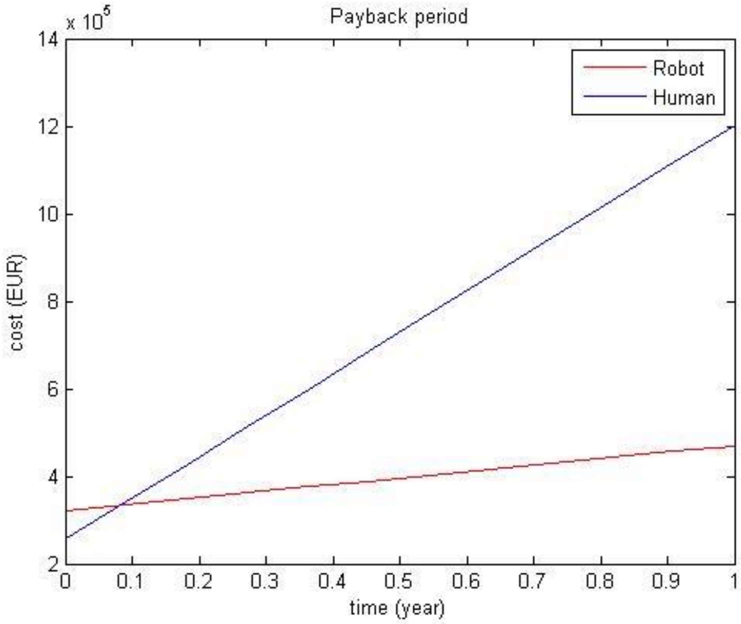


Figure 8. Payback period for the robotic system is only about a month.

10. Conclusions

Through detailed analysis of six aspects of the robotic system, it is suggested that the robotic system be less than 430kg, steel-framed and powered by lithium-ion batteries. The dynamics of leak detection was also considered through cost optimisation. Purchasing 14 robots was recommended from the optimisation process to achieve a good balance between cost and reliability of detection. This includes 2 extra robots to ensure smooth operation.

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