An economic evaluation methodology to compare the use of self-compacting concrete with normal compacting concrete

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ABSTRACT

The factors that influence the cost of Self-Compacting Concrete (SCC) and how these factors influence the construction costs are known, but the contribution of the different cost constituents are currently poorly defined. This paper introduces a systematic methodology that can be used to construct a cost model to calculate the financial impact of using self-compacting concrete on a construction project. The results are presented as cost based key performance indicators (KPI's) on a concrete related and project specific cost dashboard. The paper provides a description of the mathematical model and the results of an investigative case study. The model enables a project stakeholder to identify the optimal SCC implementation strategy for a project. It was found that SCC usage can lead to an increase in the overall construction cost, mostly due to the increased cement content, but the time saving of SCC can potentially outweigh the increased material cost due to the reduction in overheads and project duration.

1 INTRODUCTION

The implementation of SCC in South Africa is still limited despite the wide usage of the technology in developed countries. By 2007 it was only used for a relatively small number of applications and the acceptance of SCC by the South African construction industry was described as limited (Geel, Beushausen & Alexander, 2007). Not much has changed, SCC has remained a specialized concrete material and the implementation thereof in South Africa is lagging behind that of the developed world.

The fact that South Africa is not implementing SCC in the same order of magnitude as developed countries, despite the published perceived advantages, was one of the aspects that inspired this research. With the growing demand for engineering skills and decreasing resource availability, the question of why SCC is not implemented regularly, became even more apparent. It was therefore decided to investigate the financial impact of implementing SCC.

The perceived published advantages of using SCC include overall project savings on cost and time, whilst improving the quality of the hardened concrete. This study tested the first two claims on a quantitative basis.

The primary objective is to describe an accurate cost implication model that should be used to quantify the impact of the decision to implement self-compacting concrete on a construction project.

The model presented in this paper was designed to provide a better understanding of the cost breakdown of using SCC and to quantify the costs in terms of defined metrics that can be used as decision making criteria. The benefits of this model include:

1. It takes all the cost into account in the concrete and concrete placement related supply chain
2. It incorporates and quantifies the impact of time and cost related uncertainty into the final answer by means of a Monte Carlo simulation
3. The output is highly interpretable visual results that enables a reader to immediately understand the different cost constituents and their relationships with element geometry, construction environment, material costs etc.
4. The model can accommodate almost any type of concrete construction activities
5. 'Fine-grained' cost comparisons are possible since the costs for using SCC and NCC are calculated on a per element basis

A case study was used to test the proposed model and to demonstrate the value of the results and to evaluate the effects that SCC implementation can have on a project. Although the numeric values of the case study results are informative, the focus of the paper is on the type of information that is presented by the results and the ease with which the cost breakdown can be understood if the proposed calculation methodology is adhered to. This enables effective cost and even risk management since the financial impact of a decision can be fully understood.

The model output information can be used to optimize and prioritize concrete construction related cost management strategies.

2 THE COST COMPARISON MODEL FOR SCC VS. NORMAL COMPACTING CONCRETE (NCC)

The model consists of two parts, namely:

- A set of static deterministic calculations, forming the static model part, and
- a set of stochastic calculations in which a Monte Carlo analysis is used, forming the heuristic model part

The static model does not incorporate any variance and all the input variables are single data points. The static model is used to simulate the real value chain on site that exists with regard to concrete placement. The variance is simulated using the Monte Carlo method to create the heuristic model that supplements the information of the static model. This variance within the data simulates possible variations in the value of specific uncertain input parameters.

2.1 General Approach

The ideal is to perform static deterministic calculations as far as possible. The uncertain parameters of the static model are then statistically analyzed. The overall results are presented as a combination of static and probabilistic results.

Table 1: Role of static and heuristic modelling

Information required	**Cost impact and cost impact breakdown of using SCC**	**Possible variation in cost results due to inherent uncertainty**
Input parameters and required information relationship (between inputs and outputs)	Results based on single value input parameters (assume fixed input data)	Results include the possible variation in the values of uncertain input parameters
Model part created to obtain the required information	**Static model**	**Heuristic model**
Input characteristics	Fixed value inputs	Variable inputs (variability defined by a statistical distribution of possible values)
Mathematical calculation method	Static deterministic calculations	Statistical/stochastic calculations by means of a Monte Carlo simulation
Result characteristics	Fixed value results	Resulting distributions

Table 2: Sixty extractable KPI's

		Critical Performance Areas (CPA's)					**Additional performance areas**	
		Material cost	**Placement labour cost**	**Formwork cost**	**Rework cost**	**Other costs implication**	**Total cost**	**Time impact**
Elemental breakdown (KPI classes)	**Overall project specifics**	SCC and NCC	SCC and NCC	SCC and NCC	SCC and NCC	SCC only	SCC and NCC	SCC only
	Slab elements	SCC and NCC	SCC and NCC	SCC and NCC	SCC and NCC	SCC only	SCC and NCC	SCC only
	Beam elements	SCC and NCC	SCC and NCC	SCC and NCC	SCC and NCC	SCC only	SCC and NCC	SCC only
	Wall elements	SCC and NCC	SCC and NCC	SCC and NCC	SCC and NCC	SCC only	SCC and NCC	SCC only
	Column elements	SCC and NCC	SCC and NCC	SCC and NCC	SCC and NCC	SCC only	SCC and NCC	SCC only

The uncertain input parameters are modelled as static values in the first phase and then modified with statistical distributions in the second phase. The role of the static and heuristic modelling in the calculation procedure can be seen in Table 1.

Five critical performance areas (CPA's) are calculated to enable the extraction of sixty key performance indicators (KPI's). Different subsets of the sixty KPI's are of importance to different project stakeholders. The extractable KPI's are shown in Table 2.

The Monte Carlo analysis is performed after the main influence parameters have been identified for the KPI's under consideration. The distribution type to be assigned in the Monte Carlo analysis depends on the type of uncertainty associated with the specific influential input parameter that has been identified.

2.2 Model Structure

Two values are calculated for the concrete related construction cost of every planned element cast, namely the total cost when using NCC and the total cost when using SCC in the construction procedure. These costs are calculated as shown below:

$$T_{SCC} = M_{SCC} + L_{SCC} + F_{SCC} + R_{SCC}$$

$$T_{NCC} = M_{NCC} + L_{NCC} + F_{NCC} + R_{NCC}$$

With:

T = *Total element cost (R)*

M = *Material cost per element (R)*

L = *Labour cost for element placement (R)*

F = *Formwork cost per element (R)*

R = *Rework cost per element (R)*

The subscripts SCC and NCC refer to the concrete type. The implication of other costs, represented as A, will have a negative value due to its definition being an additional saving due to the use of SCC, such as savings on overhead expenses. The total cost implication of using SCC for a specific element can then be calculated as:

$$\Delta TC = T_{SCC} - T_{NCC} + A$$

The mathematical relationships in the model are illustrated in Figure 1. A sensitivity analysis is then used to isolate the most influential input parameters and a subset is chosen from the influential input parameters, based on an uncertainty criterion. The subset of uncertain and influential input parameters is used in the Monte Carlo analysis to simulate all the possible outcomes if SCC is the chosen construction material.

The model delivers a large data set as a result that can be subdivided according to the needs of the specific project stakeholder. Three types of information are contained within the results, this include:

- Total cost breakdown, into the 5 CPA's, for every KPI class (Pie chart showing total cost, and each CPA's cost contribution)
- KPI change summary to show the effect on every KPI if SCC is implemented (Bar chart showing the relative change that SCC implementation realizes)
- Total cost difference and its elemental composition

3 BRIDGE Nr. 5895 OVER THE MODDER RIVER, NEAR GEORGE: AN INVESTIGATIVE CASE STUDY

A case study was done to test the economic evaluation methodology by quantifying the decision to implement SCC on a project. The chosen project was the construction of a new bridge.

The structural design was subdivided into the basic structural elements to use the developed calculation methodology, these elements are:

- 4 concrete types (based on characteristic strength)
- 10 slab element types
- 6 column element types
- 10 wall element types

A single type of element in a specific class (such as one of the ten wall element types) comprises of all the elements in the structure with similar geometric and construction constraint characteristics.

Forty concrete casts were executed and the total volume of concrete used was 1 223 cubic metres.

Eight influential and uncertain input parameters were identified through the sensitivity analysis and included in the Monte Carlo analysis. These include:

- The percentage of concrete casts that are expected to take place in a penalties period

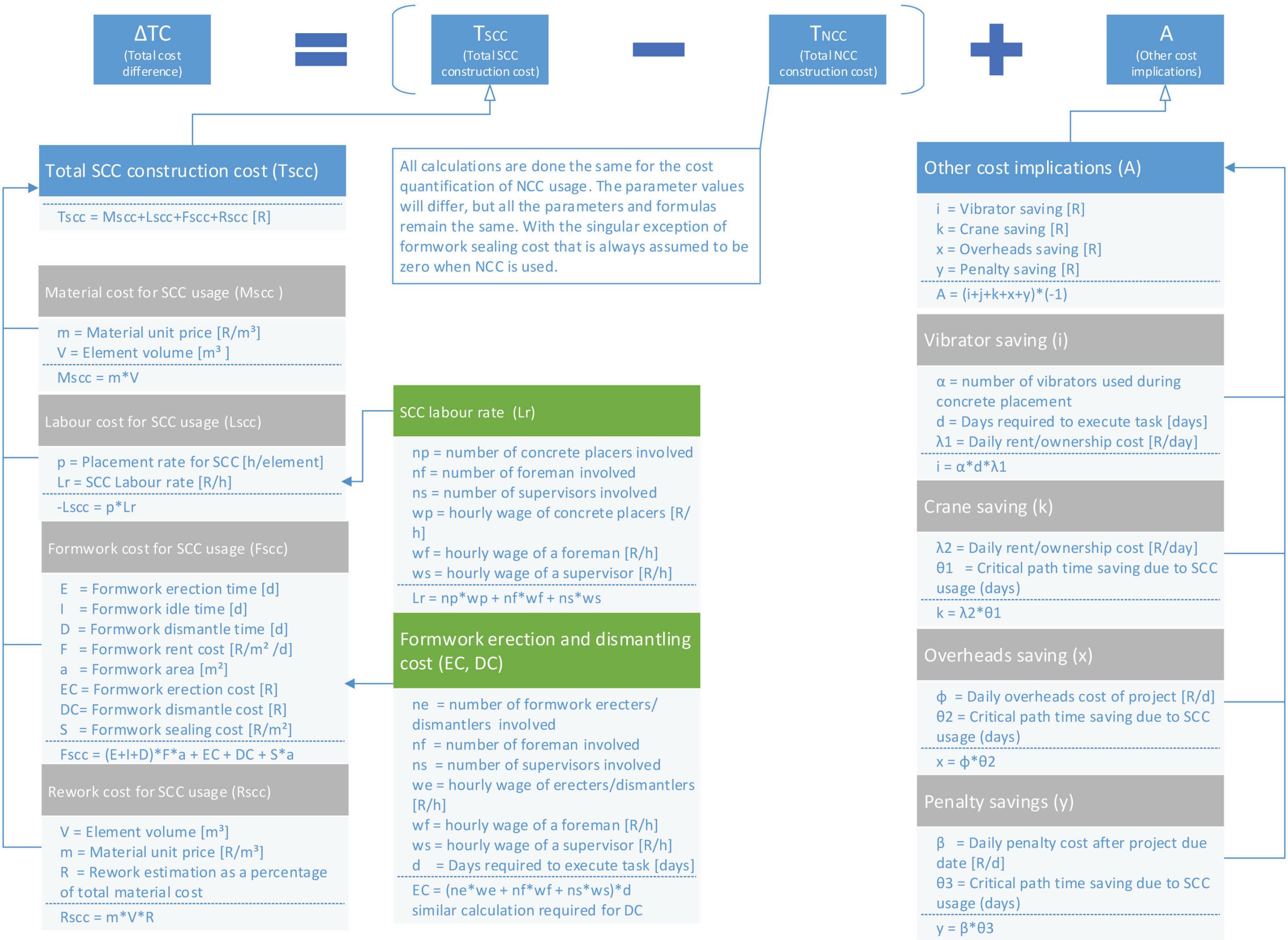


Figure 1: Mathematical relationships in the model

- The unit costs at which the four concrete mixes can be procured
- The renting time of the formwork (this includes the formwork erection time, support time and dismantling time)

4 FIRST ORDER RESULTS AND DIRECT INSIGHTS

All the results should be interpreted with two considerations in mind; what does the calculated value mean and why is it useful? The meaning of the calculated value is self-explanatory, but the value of the proposed calculation method will become evident by analyzing the type of answer obtained.

The first consideration is applicable to the results that were obtained from the case study. The calculated results are then used to show the insights that the proposed calculation method leads to and the applicability thereof.

4.1 Static results

The static results are represented in terms of the KPI's as calculated with the static model. The KPI's are the material cost, placement labour cost, formwork cost, rework cost, other cost implications, time impact and the total cost.

The overall cost implication KPI is the highest level KPI considered. This KPI comparison can be utilized by a decision maker who needs to know the total financial impact of implementing SCC on a project and then use the information as a decision criterion. Figure 2 shows the overall cost implication of using SCC, represented by the R 364 600 cost difference between SCC and NCC for the case study. The breakdown of the overall cost, into the different CPA's, can also be seen.

The calculated time saving for the whole case study project amounted to 14 days on an original construction duration of 277 days.

In a lowest bid tendering process, a contractor might reject the use of SCC based on the increase in the overall cost KPI, but a client can benefit from this information and specify SCC for a different reason. A client can opt for SCC at the increased cost since the accelerated schedule can provide a quicker return on investment (ROI). The quantification of the cost-benefit trade-off is thus important to enable a client to accept or reject the expected cost impact on construction if SCC is used.

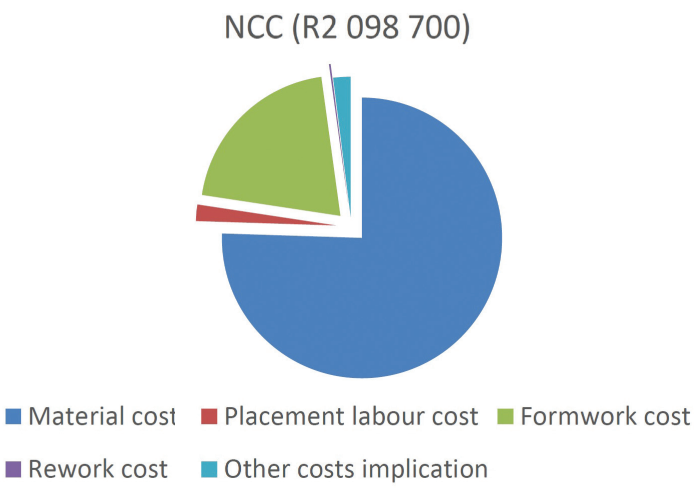
The 17.5% cost increase has a basic economic justification that can be of interest to clients and contractors. The increased price is paid for increased ease of use, better site conditions, a potentially more durable finished product, the ability to accelerate the construction phase and eventually an increase in return on investment and improved capital turnaround times.

The cost increase can be reduced by means of managerial and logistical decisions or variations in the sequence of construction tasks. More task relationship options are made possible by using SCC and the reduction in scheduling constraints can lead to increased financial viability. The reduction in material cost by the addition of cement extenders can further reduce the cost difference.

The change in the cost composition is used to identify the focus areas for cost reduction efforts. The following observations can be made from Figure 2:

1) The notable reduction in the placement labour cost contribution is attributed to the improved workability of SCC and will be a generic result for the use of SCC in most concrete applications
2) The implication on 'other costs' is not included as a cost constituent on the SCC chart (due to the definition of the KPI)
3) Rework cost is negligible in both cases due to the assumption that 0.25% of the total concrete cost is representative of the rework expense associated with NCC and SCC rework is assumed to be 0%
4) The percentage cost contribution of formwork stays approximately constant, this means that total formwork expense will increase in the same order of magnitude as the total expense
5) The decrease in rework and placement labour cost is outweighed by the increase in material cost
6) Material cost is the largest cost contributor at more than 75% of the total cost.
7) Any cost reduction in material will translate to a noteworthy saving on the total expense
8) A 14-day time saving would be the result of SCC implementation
9) The total expected cost increase is R364 611
10) If R26 050 per day (R364 600/14) was saved on overheads due to the accelerated schedule, SCC usage would have lowered the total project cost

The use of SCC would have been the more expensive option for this case study, but it would have saved time (and overhead savings are excluded from the calculations). The cost increase could have been reduced by negotiating better material unit prices or by investigating the use of cement extenders.



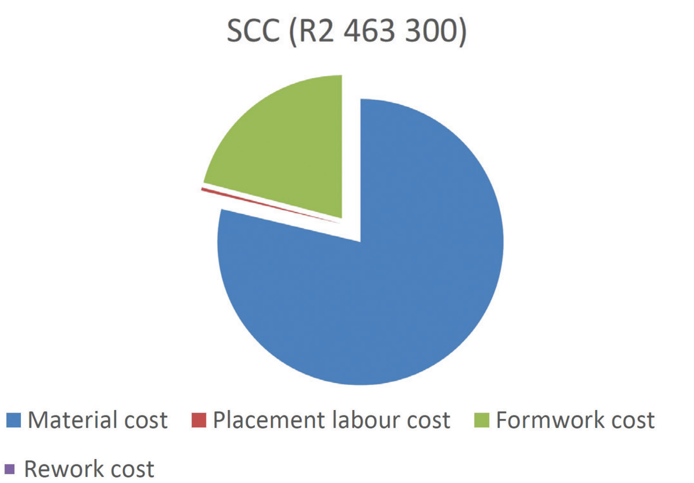


Figure 2: Overall cost comparison for SCC vs NCC

4.2 Heuristic results

After the static results have been calculated the following considerations can assist in choosing the data (inputs and KPI's) that should be included in the Monte Carlo analysis:

1) Can the input data be altered? (data such as element volume is fixed by design and cannot be altered)
2) Is there uncertainty in the source of the input data? (items such as construction time can be uncertain while formwork renting cost may be certain)
3) Does the input parameter have a large influence on the KPI? (does a 10% variance in the input parameter lead to at least 1% change in the KPI value?)
4) Is the specific project participant interested in the value of the chosen KPI? (contractors might be interested in the cost KPI's while clients might also be interested in the time KPI's)

If all four statements are true, then the KPI and the relevant input parameters should be included in the Monte Carlo analysis.

Eight parameters were identified as influential input parameters and were assigned statistical distributions. Ten thousand iterations were performed in the Monte Carlo analysis. The applicable output KPI's are calculated using the varying input values. Figure 3 shows the resulting distribution for the total cost difference of the overall project.

The estimated cost impact of using SCC is an increase of between 14% and 21% (R294 800 and R438 200), with a 90% confidence interval.

The resulting distribution can be used as part of a risk assessment for the implementation of SCC. It can help a project team to decide if they are able to accept the increased construction cost associated with using SCC for a specific concrete structure or element.

It is useful to analyze specific concrete casts to identify which elements are most suited for SCC use. The sensitivity of the individual concrete casts can be of interest to precast manufacturers or other organizations that construct small elements and who are looking for a method of optimizing the cost-quality-time trade-off.

This method of analyzing a specific KPI with the included variance in the input parameters can be done for any KPI of interest.

4.3 Case Specific Information

The parameter sensitivity analysis as calculated from the static model and the results from this analysis is case dependent and will change with varying project characteristics.

The sensitivity analysis is done to identify the input parameters that have the largest effect on the output KPI's. Three types of information can be extracted through the sensitivity analysis:

1) Identifying the top ten input parameters that have the most influence on the output KPI under investigation (cost management can be enhanced by focusing on these parameters);
2) The sensitivity of the KPI with regard to these ten influential inputs and if it is possible to lower the expected cost by managing these inputs (cost management efforts can be further prioritized);
3) Identifying the uncertain and influential input parameters to include them in the Monte Carlo analysis (Enhancing the accuracy of the results that are used to decide if SCC should be used at a project).

The results of the sensitivity analysis can be shown as tornado graphs for the evaluated KPI's. The sensitivity analysis yielded the following results for the specific case study:

- Five of the ten most influential input parameters are material unit costs;
- The SCC unit cost of externally supplied 'Mix1' is the most influential input parameter with regard to the total cost difference (Mix1 is used to construct the bridge deck, the element for which the most concrete is used in the case study);
- Mix 2, Mix 3 and Mix 4 are less influential because a smaller volume of these concrete mixes are used on site (compared to the volume used in the deck);
- The total number of concrete casts assumed to take place in a penalty period are influential to the total cost due to the savings in overheads and penalties that are dependent on its value.

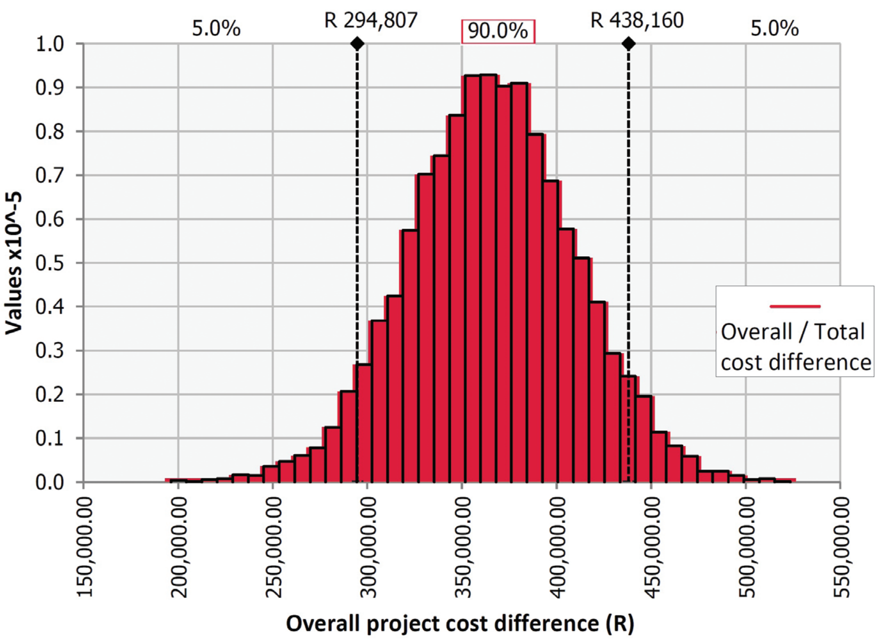


Figure 3: Probabilistic result for the total cost difference KPI

Continuing with the overall project cost difference KPI as an example, the results of the sensitivity analysis on this KPI is shown in Figure 4.

In a similar way, this can be done for any other KPI if the need should exist.

- A 10% reduction in the material unit price (from R1 565 to R1 408.50 per m³) of SCC Mix1 (used to construct the bridge deck) leads to a 32.3% reduction in the cost difference (R364 611 to R246 972);
- A 10% reduction in the material unit price of SCC Mix2 (used to construct the piling columns) led to a 13.4% reduction in the cost difference (R364 611 to R315 825);
- If a 10% cost reduction in all SCC unit prices can be achieved, it will lead to a reduction in the cost difference of approximately 55% (32.3% for Mix1 plus 13.4% for Mix2 plus 6.41% for Mix3 plus 3.01% for Mix4).

  Note: A 10% reduction in the unit price of SCC is considered since the product has higher profit margins than NCC and a smaller market base.

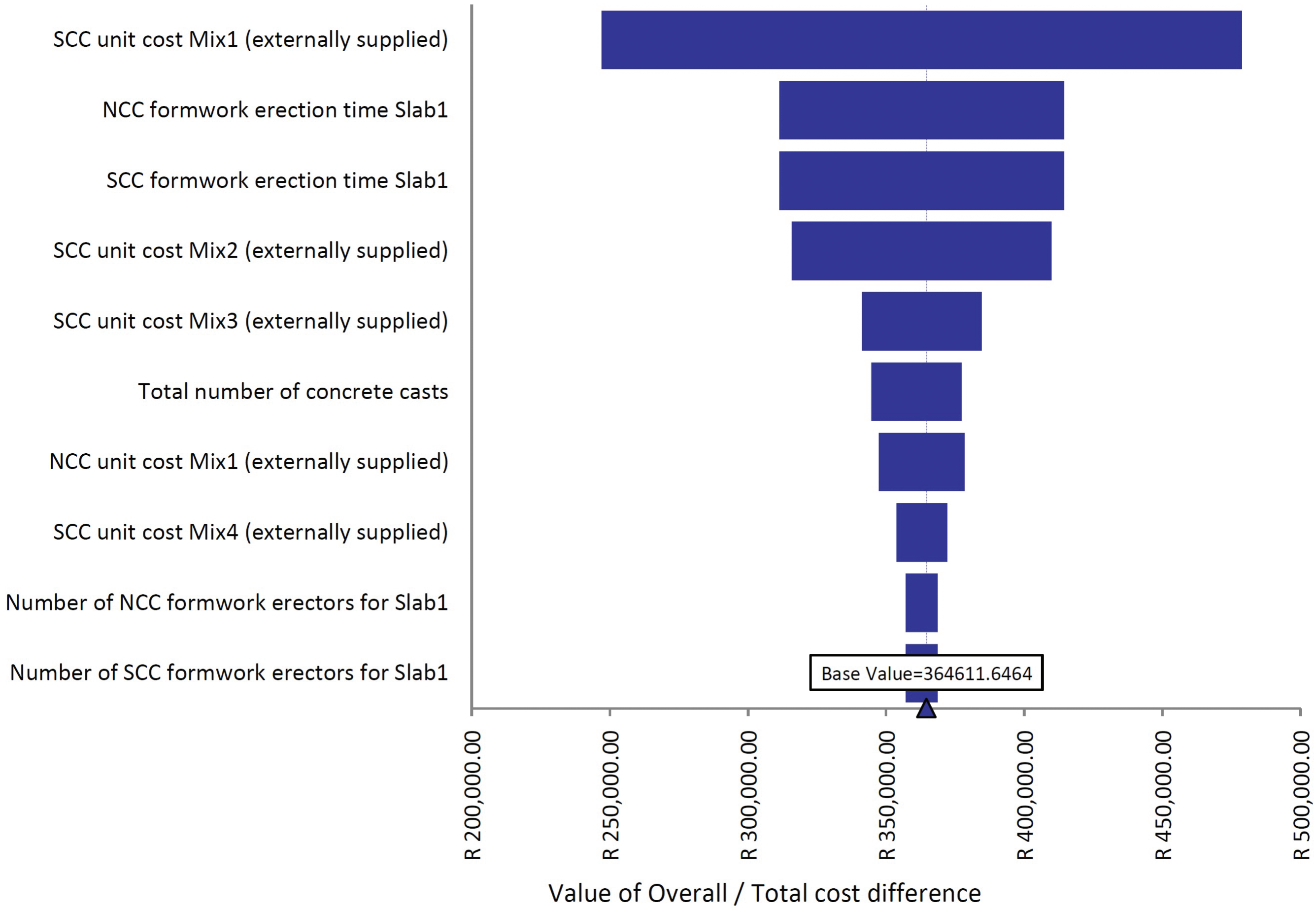


Figure 4: Sensitivity analysis of the overall project cost difference

This creates the opportunity for price negotiations, unlike NCC where profit margins are much lower and there is no room for further discounts.

- The two formwork erection rates should be disregarded (for the sensitivity analysis) due to the irregular use of the parameter in this case study
- The large cost contribution of slab elements towards the overall project cost difference (51%) is highlighted by the fact that six of the ten influential input parameters are related to the construction of Slab1, the six bridge deck spans

4.4 Generic Information

The value of breaking down the cost into the different constituents is the clarity that the breakdown provides about the following factors:

- The size of the cost contribution of every constituent towards the total cost (the total cost of an element or of the entire project).
- The extent and manner in which the size of the cost contributions changes for each constituent when SCC is implemented.
- How the cost impact information can be used to reduce the total project cost difference when choosing to use SCC.
- Identifying the results that are based on uncertain input variables and which should be included in the Monte Carlo analysis that forms part of the heuristic model.

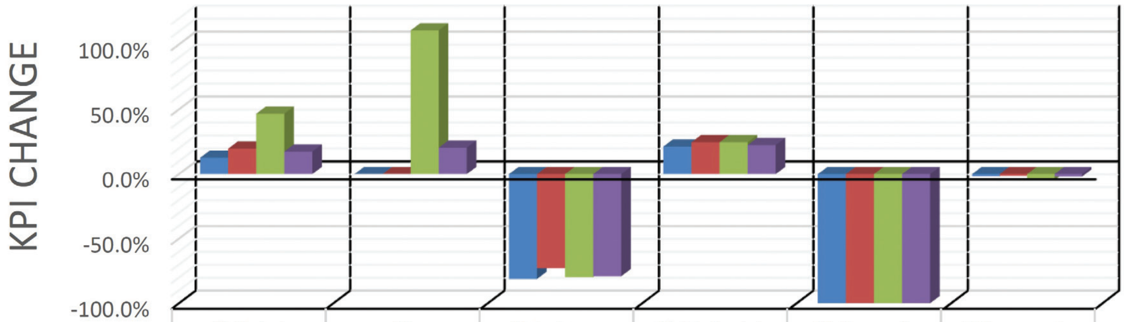
The first point is addressed by the results presented in the pie charts (Figure 2). The second point is only to some extent addressed by the pie chart representation. The exact change that will occur for every cost constituent when SCC is implemented remains unclear. The KPI change summary shown in Figure 5 shows the exact calculated change of each cost constituent when SCC is implemented on the case study project.

The information about how and to what extent a cost constituent change can be extracted from this KPI summary. The material cost difference for slab elements, the material cost difference for the overall project and the total cost difference of a slab will be evaluated as examples. The data table and the figure (Figure 5) show a 21% increase in the material cost of slab elements if SCC is implemented. This figure is a result from the model and it is based on the quoted unit prices of NCC and SCC as received from the concrete supplier.

The calculated material cost difference for the overall project is 22% if SCC is used, as shown in the data table of Figure 5. This figure is the weighted average of the change in the material cost of slabs, columns and walls (21%, 25% and 25% respectively). It is weighted in terms of the cost of the concrete volume used for each element type (based on the portion of the total concrete used to construct different element types and the cost of the specific mix design used in the construction of each element). The large portion of concrete used to construct slabs in the investigated project results in the 22% material cost increase for the overall project.

A 12.6% increase was calculated for the total slab cost of the investigated case study. This figure is also a weighted average. It is the weighted average of the cost difference in the formwork, labour, material, rework and 'other costs' as calculated for slab elements (0%, -81%, 21%, -100% and -2% respectively).

The pie charts (Figure 2) show the size (base value) of each cost constituent and the KPI change summary shows the exact change that can be expected if SCC is implemented.



	% Total Difference	% Formwork Difference	% Labour Difference	% Material Difference	% Rework Difference	Other costs implication as % of total cost
Slabs	12.6%	0%	-81%	21%	-100%	-2%
Columns	19.6%	0%	-73%	25%	-100%	-1%
Walls	46.6%	111%	-80%	25%	-100%	-5%
Overall	17.4%	20%	-79%	22%	-100%	-2%

KPI CATEGORIES

Figure 5: KPI change summary

The third point, how to reduce the total project cost difference with this information, can be addressed in the following ways:

- Based on the large contribution (refer to pie chart information in Figure 2) of material and formwork cost, as well as the increase in the percentage cost contribution if SCC is implemented (KPI summary), cost reduction efforts should be focused on these KPI's;
- Formwork costs can be reduced by negotiating lower unit prices for renting the formwork;
- Material costs can be lowered through unit price negotiations and/or the addition of cement extenders.

5 SECONDARY DEDUCTIONS AND CONSIDERATIONS FOR SCC USAGE

The following observations and deductions can also be made from the results and evaluation methodology:

- The labour intensity (man-hours per cubic metre of concrete placed) required to construct an element will indicate whether or not reductions in labour costs is worth pursuing (higher man-hours per cubic metre of concrete placed means a higher significance of labour cost reductions);
- The labour intensity usually rises as the size (volume) of an element reduces;
- A small element with a high labour intensity will render reductions in labour cost the most significant since these elements have the highest labour cost per cubic metre of concrete. This element type thus provides the highest financial incentive to be constructed with SCC since it will provide the most financial benefits in terms of labour savings;
- The outer surface to volume ratio will indicate whether or not reductions in formwork costs is worth pursuing;
- A larger outer surface to volume ratio indicates a larger contribution of formwork cost to the total cost and hence an increased importance of managing the formwork cost;
- The time that the formwork supports the fresh concrete will provide an additional indication of whether or not reductions in formwork costs is worth pursuing;
- If the formwork support time is short, then the percentage that the formwork cost contributes to the total cost is lower since the formwork is rented for a shorter time (e.g. vertical elements);
- The outer surface to volume ratio and the formwork support time should be considered together to make a final estimation on whether or not to pursue cost reductions for formwork;
- Any reduction that can be realized in the material cost will significantly enhance the economic viability of SCC;
- Off-shutter and high-quality concrete finish specifications will increase the contribution of rework cost to total cost. SCC can be used if a contractor is inexperienced with these specifications;
- The construction of smaller elements is more labour intensive (more man-hours per cubic metre of concrete used) than large elements. As elements get smaller, the contribution of labour cost increases;
- Projects with small and repetitive elements will show a higher labour cost contribution and a lower overall cost difference if SCC is implemented.

These findings are supported by the regular implementation of SCC in the precast industry in South Africa.

Considering the connection between element size and financial viability, hybrid-concrete construction projects can benefit from SCC implementation. The repetitive placement labour saving on small elements, manufactured in the precast yard, will lower the total cost of a project.

6 CONCLUSIONS

The results of the proposed economic evaluation methodology can be used to investigate the overheads that will render SCC advantageous due to the acceleration in the project schedule. The break-even figure for the investigated case study for overheads was R26 050 per day. If the overheads of the project were higher than R26 050 per day, SCC implementation would have reduced the total concrete related project cost.

A sensitivity analysis showed that a 10% reduction in the unit price of SCC would halve the total cost difference between the SCC and NCC options.

The low usage of SCC in the South African construction industry, compared to certain developed countries can be attributed to the material cost increase that SCC usage incurs for a contractor. When this increase is considered, together with the lowest tender award scheme and the fact that the client is the long term benefactor of SCC usage, it is understandable why SCC is not regularly used in South Africa. The relatively cheap labour and the absence of other restrictions (such as noise limits and strict equipment restrictions for urban areas) is a structural difference between the South African industry and those countries with higher SCC utilization. The structural differences, combined with the lowest tender awards structure in the South African construction industry, deprive the industry of incentives to harness more time-efficient and higher workability materials at an increased cost.

The cost difference between NCC and SCC can be minimized by means of cement extenders and logistical changes in the construction process. This can lead to increased SCC usage in the South African construction industry.

The methodology explained in this article can be used to identify the areas where cost management and cost reduction efforts can be focused for the greatest advantage, and the minimum risk, on a specific project.

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