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Framework for Sustainable Risk Management in the Manufacturing Sector

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Abstract

Risk management is a huge challenge for business managers especially in the manufacturing engineering sector, and if not proactively controlled can lead to under performance and sometimes cessation of activities for some companies. It is common knowledge that poorly managed risks can have an adverse effect on performance while proactive and systematic control of key risk variables in a business environment could generate successful outcomes. The work carried out here has developed a framework for risk management affordable and suitable for use especially by small and medium size enterprises in the manufacturing sector. Using a combination of Bayesian Belief Network (BBN) and Analytical Hierarchical Process (AHP) search algorithms, it was possible to search and identify key risk indicators that could undermine business performance (measured in terms of cost, time, quality and safety) from a system database, and thereby manage (monitor, identify, analyse, reduce, accept or reject their impact) them. The conclusion drawn from the study is that risk management for a manufacturing process can be successfully achieved if risk factors which have a negative impact on project cost, quality of delivery, lead cycle and takt time and health and safety of workers can be identified using BBN and minimised using the framework developed in this study.

Keywords; Risk Management;Manufacturing;Framework;Bayesian Belief Network;SMES;Software;Performance

1. Introduction

This research paper will start by presenting background information to risk management in the manufacturing sector followed by review of the literature for state of the art knowledge in this subject area. An algorithm for generic risk management system will be presented highlighting the various stages from establishing the risk context, assessment, evaluation and managing it. Finally, a risk management framework will be developed showing the sequence for assessing potential risk factors associated with the typical manufacturing process, and then identifying the key risk indicators using the Bayesian Belief Network (BBN) that could affect performance measured in terms of cost, time, quality and safety.

The manufacturing industry is the bedrock of any nation's economy and therefore should be nurtured to a high level of standard and maturity in order to be robust, self-sustaining, and self-reliant. The industry in the present day is facing many challenges because of competition, legislation, international standards, globalisation and changes in technology. Businesses also need to be agile to respond rapidly to incessant customer needs and react to a dynamic production environment. In order to achieve the aforementioned objectives the manufacturing sector would need to be aware and conscious of a wide variety of risks especially linked to human resource, organisational, technological, economical, political, environmental and legislation. Risk management therefore, could pose a huge challenge for business managers especially in the engineering sector, and if not proactively controlled can lead to under performance and sometimes cessation of activities for some companies. It is common knowledge that poorly managed risks can have an adverse effect on performance while proactive and systematic control of key risk variables in a business environment could generate successful outcomes.

The following research questions would be relevant to developing a suitable framework for risk management especially in the manufacturing sector.

(1) How will the rapidly changing risk landscape affect

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future planning for internal audit and for the organisation?

(2) Is the outside-in view of risk the same as the view from the inside out?

(3) Are return on investment for innovation and research and development programs effectively monitored?

(4) Is the organisation proactive to identifying rapid on set of cyber-attacks, global supply/demand changes, onset of geopolitical risk, raw material/energy price volatility, pricing, fraud and corruption,

(5) Has an appropriate cross-functional ownership been identified for mitigation strategies for risks that cross-Organisational boundaries?

(6) How will IT risks be identified and addressed timely in the future e.g., those associated with security, social media, data loss, and other emerging risks?

Based on the research questions outlined above, **the aim of the research carried out here is to develop a framework for sustainable risk management system suitable and affordable by small and medium size enterprises in the manufacturing sector.** The research objectives therefore are to:

- Identify risk factors that could affect performance in manufacturing enterprises and specifically SMEs
- Highlight key risk indicators that that could impact on performance and propose a methodology to manage such risks
- Design a framework that should form a basis for development of a risk management system in the manufacturing sector

2.0 Literature Review

2.1 Typical Risks Associated with the Manufacturing Sector

Manufacturing companies seek to reduce the incidence of occupational risks while they strive to increase efficiency and productivity. To avert pressure on workers, employers sometimes adopt a variety of solutions such as job rotation, add more employees on the same task, or decrease the pace of work. In other cases they could design ergonomic workstations [1] or introduce advanced manufacturing technology to minimize repetitiveness in the production environment. In this context, collaborative robots have become a major trend that provides fast and long-term solutions to ergonomic problems. In a case study, collaborative robots were found to reduce the incidence of occupational risks among the employees of an assembly station increasing safety and improving performance of the entire assembly line.

Giannfetti, C and Ransing, R.S [2] developed a novel algorithm which embeds risk based thinking to quantify uncertainty in manufacturing operations during tolerance synthesis process. They used penalty-guided methodology to mathematically represent deviation from expected results and then solve tolerance synthesis problem by proposing a quantile regression tree approach. The focus of the work is to develop a robust and general purpose method for tolerance synthesis to quantify the combined effects of process variables on the quality output without making distributional assumptions and thereby overcome the linearity assumption of previous algorithms for risk based tolerance synthesis. They applied a non-parametric estimation of conditional quantiles of a response variable from in-process data allowing process engineers to discover and visualise optimal ranges that are associated with quality improvements.

Designing a work environment to meet the needs of employees and job requirements is a fundamental factor to enhance productivity, while improving operators 'health and safety at work. Andreea Dumitrescu, Dana Corina Deselnicu [3], identified the risks associated with human labour within small and medium enterprises operating in the manufacturing industry. Compared to other industrial sectors, manufacturing processes involve high level of interaction between operator and equipment, These emerging risks are sometimes generated through human resource errors, insufficient task description, working with dangerous equipment, and hostile physical / environmental factors such as work space lighting conditions, level of noise, exposure to radiations, intensity of vibrations, air purity, and temperature condition.

The health and safety impact of robot proliferation in the present day manufacturing environment cannot be underestimated. More than 3 million industrial robots will be in use in factories around the world by 2020, according to the International Federation of Robotics. Robots have the potential to offset the talent gap and increase productivity, but risks abound. Liability issues surrounding product defects, personal injury or property damage are murky at best, and manufacturers could be forced to defend themselves against claims actually caused by hardware or software defects.

In a more recent study, Nazli G. Mutlu, Serkan Altuntas [4] assessed occupational risks in Turkish manufacturing systems demonstrating data-driven models. Supply chain risk management (SCRM) consists of risk identification and modeling, risk analysis, assessment and impact measurement, and risk management. It is desirable that the evaluation of performance of a supplier be aligned with the performance evaluation of the supply chain. This would require the use of similar metrics to evaluate the performance of the suppliers and the supply chain. One approach widely adopted by the practitioner community to supply chain performance evaluation is the Supply Chain Operations Reference (SCOR®) model which proposes a hierarchy of performance measurement metrics that evaluates five dimensions of performance: reliability, responsiveness, agility, cost, and asset management.

Suthep Butdeea, Puntiva Phuangsalee [5] modelled uncertainty and risk associated with the supply chain activity of bus body manufacture in Thailand which is normally subcontracted. They studied 6 companies and applied AHP and FAHP methodology to propose risk management system focusing on Plan, Source, Delivery, Make and Return.

Marko Djapana, Ivan Macuzica, Danijela Tadica, Gabriele Baldissone [6] developed a prognostic risk assessment tool (PgRA) proposed for the quantitative analysis of the effects of HOT(human, organisational and technological) factors on occupational risks, mainly for the manufacturing sector (production, assembly, transport, etc).Using the PgRA tool, managers can predict the potential risk level and its reduction through the corrections of the sub-factors. This allows risk based decision making to be performed by the combination of measures and actions to be undertaken in order to lower the occupational risk level, with reference to a cost/benefit analysis. This paper presents a discussion of what makes a risk assessment tool suitable for manufacturing sector (SMEs predominately) and then proposes a tool based on fuzzy logic and prognostics along with a case study of its implementation in a manufacturing company in Serbia. They recommend the use of this tool to predict potential risk level before implementation of the planned measures. The authors emphasised on the human, organizational and technical/technological (HOT) factors, which were recognized to be both precursors, and barriers to safety management, particularly in an automatized environment.

2.1.1 Human risk factors

Under human factors, cases of accidents, injuries, work environment could all contribute to underperformance. Inexperienced workers in a manufacturing environment are at a high-risk for accidents and injuries especially within their first six months of employment. Increased overtime and 24/7 operations also lead to fatigue, sharply increasing the risk of serious injuries or fatalities. More than 3 million industrial robots will be in use in factories around the world by 2020, according to the International Federation of Robotics [6]. While robots have the potential to offset the talent gap and increase productivity, their use could pose abundant risk especially in manufacturing environments. Liability issues surrounding product defects, personal injury or property damage are murky at best, and manufacturers could be forced to defend themselves against claims actually caused by hardware or software defects.

2.1.2 Organisational risk factors

Supply chain partnerships, quality assurance, leadership management, international business environment and competition are some of the organisational key risk indicators that affect business performance. In the era of lean manufacturing, projects are typically time, cost and quality sensitive, leaving little room for delays. Manufacturers that can't deliver on their promises because of a supply chain stall risk losing out on millions of dollars in potential revenue and profit.

Anything from grounded flights to cargo theft to quality control issues can impact the flow of goods from a supplier. It is always advisable to source a reliable back-up supplier to fill the gap when there is disappointment from a regular supplier. Otherwise, operations could halt, leading to losses and damaging a company's reputation.

Even with long term reliable vendors for many years, the steady increases in volume of demand from clients and the frequency and severity of natural catastrophes these days could affect the reliability of a key vendor.

2.1.3 Technology risk factors

Technology related risk factors such as technology obsolescence and uncertainty, cybersecurity, intellectual property and resource efficiency, and manufacturing quality are key to underperformance in manufacturing enterprises. Industry 4.0, or the Industrial Internet of Things gradually absorb traditional manufacturing into the technological and connected world. The overall goal is increased automation, improved communication and monitoring, along with self-diagnosis and new levels of analysis between machines and systems. However, there are also challenges to achieving this in a manufacturing environment. Consequently, new frameworks of cyber security need to be developed to protect people, physical assets, as well as customer and intellectual property data. A smart factory, fully integrated and connected with other factories all over the world, makes for an all-too appealing attack target. In a 2016 survey, 31 percent of manufacturing respondents admitted they had never performed a cyber risk assessment of their industrial control systems **[6]** But cyber security has never been a more vital part of manufacturing operations. Cyber security firm Malwarebytes tracked a 90 percent increase in the number of detected ransomware attacks in 2017, noting that the 2017 monthly rate of ransom-related attacks increased up to 10 times the rate observed the prior year.

Security vulnerabilities increase the risk of hackers tampering with systems or even shutting down an entire production line until their demands for payment are met.

Maintenance of these modern systems presents additional risk exposure. Current maintenance personnel don't always receive adequate training and many are at least partly self-taught. The most knowledgeable and experienced among them are at or near retirement age. Smart factories without adequately trained maintenance staff run the risk of extended downtimes and lost profits.

2.1.4 Economic / Political / Financial risk factors

The major economic and political risk factors include cash flow, delayed payments, inflation, financial capital (debt / equity), interest rate, tariff wars, political instability, terrorism **[6].** Manufacturers relying heavily on foreign steel and aluminium will face significant cost increases, which would likely cut into profits and potentially even spur layoffs. For instance, U.S. steel prices are almost 50 percent higher than those in Europe or China, and its prices appear to be volatile. Retaliatory tariffs from the EU, Canada and Mexico will also be a blow to many manufacturers exporting goods to the USA. Adequate risk management put in place to guard against these factors should enhance business performance.

2.1.5 Environmental risk factors

Manufacturers are conscious of the level of emission and effluent discharge from factory premises and could be fined or stopped from trading, Oil and gas processing companies are also at risk of emitting chemical / hazardous spills and gas flare from their premises.

2.2 Risk based tolerance synthesis and uncertainty quantification

Gianfetti and Ransing [2] have proposed an algorithm which defines the relationship between risk based tolerance synthesis and uncertainty quantification. They define tolerance synthesis as adjustment of ranges of process parameters in order to reduce the variability of a given response, so that process variation is kept ‘‘close” enough to the optimal values. The requirement to achieving tolerance synthesis is to develop and test hypotheses regarding how variability of factors affects process responses. By so doing it is possible to predict process robustness. Given the complexity of multi process manufacturing, attempting to discover the relationship between process factor and responses using traditional methods like least squares regression could be very challenging and would lead to models that are sub-optimal. Mathematical formulation of the tolerance synthesis problem is feasible and can be solved with quantile regression. The major steps of the algorithm for tolerance synthesis and uncertainty quantification are summarised in Figure 1

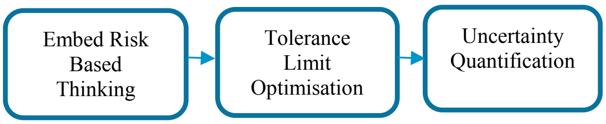

Fig. 1.Algorithm consists of three steps: (a) Embed risk based thinking; (b) Tolerance synthesis and (c) Uncertainty quantification

3.0 Generic Risk Management System

Risk is defined as combination of severity (how hard it is when it happens and probability of an event (how often it happens) - Frequency of event x consequence of hazard [7] ALARP as low as reasonably practicable principle recognises that there are three broad categories of risk Risk identification gives platform for preventive and/or proactive measures, rather than measures implemented based on prescriptive thinking.

Eq. (1) is used to express risk in quantitative manner, which will be used for decision making process

$R = LO \times DPH \times FE \times NP$ (1)

Where

R – Risk level,

LO – Likelihood of occurrence of potential harm,

DPH – Degree of potential harm,

FE – Frequency of exposure and

NP – No of persons exposed

(1) Negligible risk - broadly accepted by most people as they go about their everyday lives
(2) Tolerable risk - not rather have the risk but it is tolerable in view of benefits obtained by accepting it. The cost in inconvenience or in money is balanced against the scale of risk and a compromise is accepted
(3) The risk level is so high that we are not prepared to tolerate it. The losses far outweigh any possible benefits

Figure 2 shows a generic risk management system broken down into five stages;

- Establishing the context of the risk and the potential hazard exposure
- Risk assessment which involves risk identification, risk analysis and evaluation (is it worthwhile, cost benefit analysis). The purpose of the risk profile is to establish where the greatest vulnerabilities lie and what the probability of disruption is. It then ranks and analyses the potential risks.
- Risk treatment which could be; reduce, avert, transfer, mitigate, retain the risk or if it is an opportunity to exploit, share, enhance, or ignore it.
- Monitor and Review
- Communicate and consult
- Risk Indicators (KRI)

Risk indicator is a metric used to monitor identified risk exposures over time in a business environment. It measures the amount of exposure to a given risk using exposure indicators. To counter, minimise or mitigate the risk, a control is put in place and it is essential to monitor the effectiveness of the control plan using control effectiveness indicators. When the risk exposures are being managed, business performance is enhanced monitored by performance indicators. Risk indicator needs to have a relationship with the specific risk whose exposure it monitors. For instance, frequent customer complaints is a risk indicator of process errors within a system

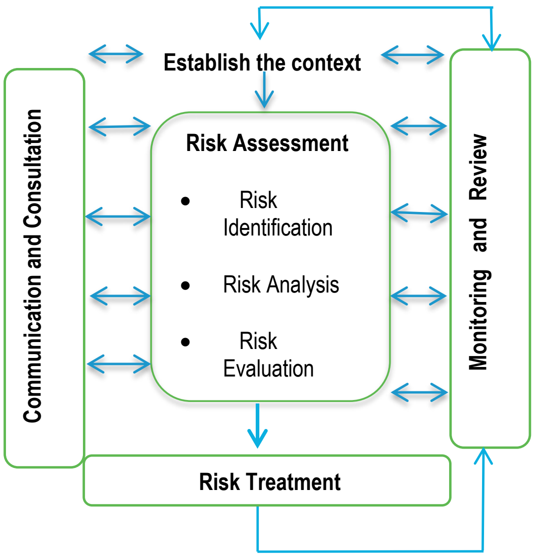

Figure 2: Generic Risk Management System

3.1 Key Risk and Key Performance in Manufacturing Risk Management

- Performance Indicators (KPI)

Performance indicator is a metric that measures performance or the achievement of targets

It is applicable to finance as well as operational risk environment. It measures performance in terms of specific targets set for risk exposure reduction, minimisation and mitigation. A typical example of performance indicator is the no of hours of information technology system outage as a result of the system being affected by virus or the percentage of items in a production line containing faults or errors. Consequently, in a production environment, risk varies inversely as performance

4.0 Research Methodology

The research methodology for this study combines information obtained from a comprehensive review of the literature on risk management focusing mainly on the manufacturing sector, secondary data from relevant sources all complemented with survey from experts and focus groups in the manufacturing sector. This enabled the development of sustainable enterprise risk management framework.

The study also applied Bayesian Belief Network (BBN) or Bayesian Network or Belief Network which is a Probabilistic Graphical Model (PGM) that represents conditional dependencies between random variables through a Directed Acyclic Graph (DAG). It is a graphical framework for modelling uncertainty and has a background in statistics and artificial intelligence and was first introduced in the 1980s for dealing with uncertainty in knowledge-based systems. They have been successfully used in addressing problems related to a number of diverse specialties including reliability modelling, medical diagnosis, geographical information systems, and aviation safety management among others. Bayesian Networks are applied in many fields. The main objective of the network is to understand the structure of causality relations that can be constructed for instance in a manufacturing environment to identify relevant risk factors that could affect performance.

The simplest form of Bayes' rule states that:

$$P(A|B) = P(B|A) \cdot P(A) / P(B)$$

$$P(A|B) = P(B|A) \cdot P(A) / P(B|A) \cdot P(A) + P(B|A') \cdot P(A')$$

If A represents an uncertain event, A' the non-occurrence of A, and B is a piece of relevant information, then $P(A)$ is the prior probability of the event A, while $P(A|B)$ is the posterior probability of A, which includes the state of knowledge given that B occurs. So, Bayes' rule can be used to incorporate experience in the calculation of probabilities for risk exposure in the manufacturing environment. [11].

Lei Yang Jay Lee [12] applied Bayesian Belief Network (BBN) to investigate the causal relationship among process variables on wafer quality during the manufacturing process. By building BBN models at different periods of the process, the causal relationship between control parameters, and their influence on wafer can be both qualitatively indicated by the network structure and quantitatively measured by the conditional probabilities in the model. Using BBN probability propagation, it was possible to diagnose root causes when bad wafer is produced; or even predict the wafer quality. Trucco, Cagno, Ruggeri, and Grand [13] developed a Bayesian Belief Network (BBN) to model the Maritime Transport System (MTS), by taking into account its different actors (i.e., ship-owner, shipyard, port and regulator) and their mutual influences.

4.1 Sustainable Enterprise Risk Management Framework for the Manufacturing Sector

Figure 3 shows the sustainable enterprise risk management framework underpinned by long term organisational visions and objectives. The framework is bottom up and starts with the identification of relevant risk indicators associated with critical risk factors. Odimabo and Oduoza [8, 9] identified over 200 risk factors affecting business performance in the construction sector. In the manufacturing sector the indicators have been associated mainly with Human, Organisational, Technological, Economic/Financial/Political, Environmental and Legal factors. Other indicators could be in Finance, Social, Innovation and Growth, Internal Business Process, Health and Safety which could be sub indicators for the six risk indicators mentioned already. Within each risk indicator are the large variety of risk factors, which are symptomatic of why risk occurs within that indicator. The next stage in the framework development involves analysis of the implications of the various risk factors on enterprise performance, Where a risk factor is successfully managed it could enhance performance and on the other hand could undermine performance and productivity if the probability of occurrence / severity is high. It is essential to identify the relationship between the risk indicators / factors and Performance. In the manufacturing sector, certain risks are relevant and more likely to affect business outputs which are predominantly cost, quality, human safety and time related. Overall, the impacts could be cost overrun, time overrun, human safety compromised or substandard quality of delivery. However, identification of key risk indicators with associated risk factors early enough either prior or during the early stages of the project could result in steps taken to mitigate, manage or even eliminate the risk entirely in such a way that it doesn't affect the key performance indicator (KPI). At the hierarchy of the framework are the common critical measures of business performance and productivity in the manufacturing sector: ɔst, time, quality and safety related metrics.

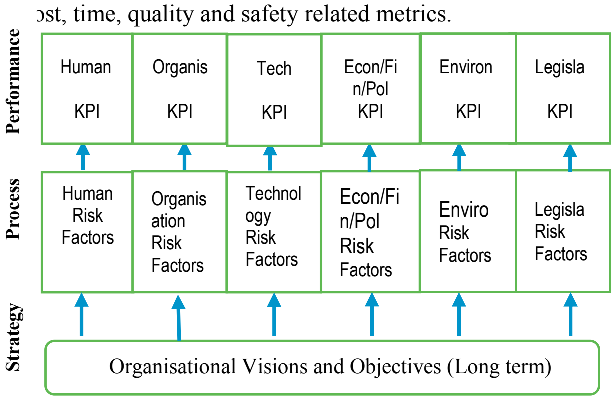

Figure 3: Sustainable enterprise risk management framework

Figure 3 shows that at the business performance measurement level the risk factors for the various indicators could interact. For instance risk factors associated with human, organisational, technological, economical / political, environmental and legal can impact on cost, time, quality and safety performance outputs in a variety of ways.

5.0 Discussion

Figure 4 shows a comprehensive presentation of risk factors broken down mainly into Human, Organisational, Technology,

Human (Health and Safety)	Organisatio	Techno	Econ / Finan/ Politic al	Enviro n	Legislat ion
Accidents	Supply chain / partnerships/ Third party vendors	New product / customer need	Cash flow	Emissio n	Contract
Injury	Competition	New process / customer need	Delayed paymen ts	Effluent	Dispute
Process safety	Total productive maintenance	Patent	Budget	Landfill waste	Legislati on
Work gear	Quality assurance	Intellectu al property	Inflatio n	Weather	National laws
Temperatu re	Care for the community	Technol uncertain ty	Interest rate	Incinerat ion	Internat laws
Pressure	Subcontractin g / time management	Cybersec urity	Financi al capital	Tempera ture	Profess/ ethics
Humidity	Training of workforce	Productio n quality	Debt/Eq uity	Pressure	Standard
Noise	Labour skill	Material quality	Econom ic stability	Humidit y	Warranty
Diseases	Internat. business environ/ Emerging markets	Circular economy	Political stability	Flood	Claims
Explosion	Culture	Resource efficienc y/Lean	War/Co nflict	Chemi / hazard spill	Change requirem ents
Vibration	Gender / racial balance	Manufact uring technique	Terroris m	Earthqua ke	Taxation
Ergonomic s	Leadership/ project mgt	Technol obsolesce nce	Cost manage ment / tariff wars	Fire	Directora tes

Figure 4: Human, Organizational, Technical/Technological, Environmental and Legal (HOTEEL) Risk Factors Associated with the Manufacturing Sector

Economic / Financial, Political, Environmental and Legislation. While the risk factors listed under each category are not exhaustive they have been identified as crucial and could be characteristically generic for most manufacturing process environments. Most risk factors affecting performance especially in the manufacturing sector are deemed to be covered under these six categories.

Figure 5 shows characteristic performance measures affected by risk factors in the manufacturing sector. It is assumed that business performance in the manufacturing sector are commonly measured in terms of cost, time, and quality of delivery and also safety of employees and other stakeholders

Figure 6 shows the framework that should guide sustainable risk management in the manufacturing sector to enhance performance. Performance indicator is defined as a metric that measures performance or the achievement of targets It is applicable to finance as well as operational risk environment. It measures performance in terms of specific targets set for risk exposure reduction, minimisation and mitigation.

A typical example of performance indicator is the no of hours (time related performance measurement) of information technology system outage as a result of the system being affected by virus or it could be the percentage of items in a production line containing faults or errors (quality related performance measurement) [10]. For instance in a production environment, negative risk outcomes vary inversely as business performance. The risk management prototype stores a large data base of risk factors associated with manufacturing sector classed (according to Figure 4) under Human, Organisation, Technology, Political / Financial / Economic, Legislation, and Environment.

Cost Related Risk Factors	Time Related Risk Factors	Quality Related Risk Factors	Safety Related Risk Factors
Capital Outlay	Labour skill to complete in time	Labour skill to perform specialist tasks	Exposure to fumes / radiation
Cash flow	Lead time for product / process delivery	State of the art technology / and equipment maintenance	Working condition (temperature, vibration, noise)
Payment to contractors	Reliability of specialist equipment	Quality of delivery to clients and customer support	Offshore production
Accuracy of cost estimates	Third party vendor responsiveness to supply of materials	Reliability of basic infrastructure	Disease
Cost visibility in international business environment	Consistency of manufacturing takt and cycle times	Quality of materials from third party vendor	Flood and earthquake
Cyber security costs	Cyber-attack impact on time	Software performance due to cyber attack	Personnel safety from cyber attack and terrorism

Figure 5 Performance Measures Affected by Key Risks in the Manufacturing Sector

Depending on the manufacturing operation, the sequence of risk management activities is broken down into three sections.

(1) Identification of key risk indicators (KRI) from potential risk factors that underpin enterprise performance in that sector. This is achieved using algorithms such as Bayesian Belief Network (BBN), Probabilistic Neural Network (PNN), Analytical Hierarchy Process (AHP) .
(2) The key risks indicators that could impact on cost, safety, quality and time management in the manufacturing process are critical.
(3) Different combinations of the key risk indicators interact and could impact on one or more of the performance indicators (Table 5).

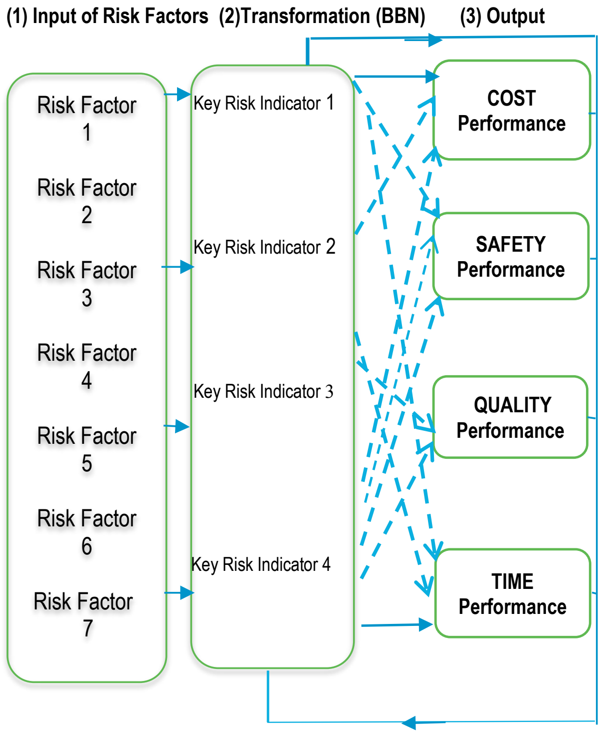

Figure 6 Framework for Sustainable Risk Management Driven by Bayesian Belief Network (BBN)

5.1 Case Study - Application of Bayesian Belief Network for Risk Management in Construction Engineering Sector:

This was achieved by identifying risk factors affecting a typical manufacturing process selected from Table 4 depending on whether they are human, environmental, organisational, technological, economical, legislation etc. Risk factors can be interdependent and interactive. For instance, human injury (human factor) could be linked with poor labour skill (organisational factor) which resultant impact on cash flow (economic factor). This dependency therefore generates Bayesian Belief Network search for key risk indicators and depending on their weighting (strong, medium and weak) would highlight the key risk indicators. Continual progression of the network search based on the risk factors and key risk indicators will lead to a final outcome where it is easily identifiable which battery of risk factors impact on the performance measurement objective; **Cost, Time, Quality or Safety.** It is also possible that two performance objectives could be affected by a combination of several risk factors. Similarly, a single risk factor such as cash flow can affect all four performance objectives. Figure 6 shows Framework for Sustainable Risk Management Driven by Bayesian Belief Network (BBN) highlighting the connectivity between risk factors, key risk indicators and performance objectives. Risk factors that directly affect performance are referred to as proximal factors in a BBN model while the other risk factors that indirectly affect project performance are called distal factors

Netica software has been used to drive BBN in order to identify network of risk factors and the relationship between them in a graphical model [10]. It becomes easy to trace relevant risk factors and establish the cause and effect relationships.

A typical example of how BBN model supports risk management in a construction engineering project is shown in Figure 7. The cause and effects for instance of inaccurate design could lead to incomplete and inaccurate estimate which in turn leads to poor quality outputs and time overruns. Typical proximal risk factors leading to time overrun were also identified to be quality problems, cost overruns. Cost overruns were found to be linked directly to fluctuation of material prizes and inappropriate leadership style.

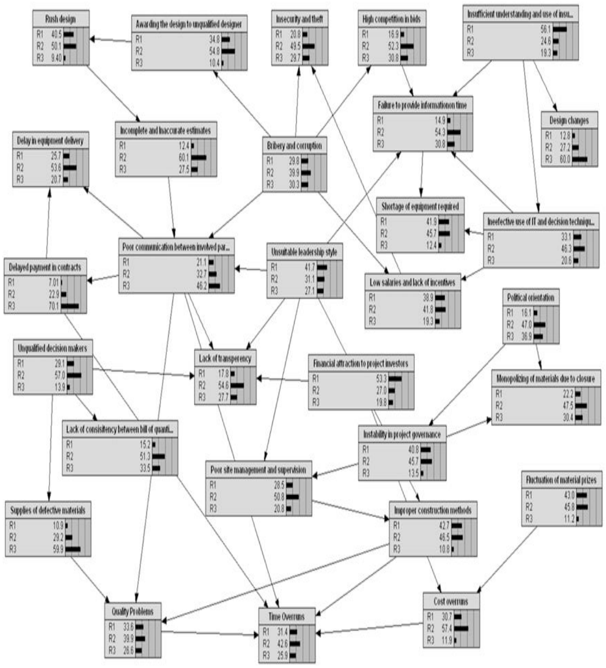

Figure 7 Bayesian belief network used in risk management

6.0 Conclusion

Risk management is essential to minimise negative influence on performance in any sector including manufacturing. The approach to risk management is to identify, analyse / assess impact and if possible to manage the risks, otherwise accept the risks. The study carried out here has developed a conceptual frame work that will enable development of risk management capable of managing varieties of risks in the manufacturing sector with a view to enhance performance. The key risk indicators that could impact on cost, safety, quality and time management in the manufacturing process are critical. Different combinations of the key risk indicators interact with each other and could impact on one or more of the performance indicators. Generally, business performance in the manufacturing sector measured in terms of lead and cycle time for instance could have a knock on effect on manufacturing cost, quality of delivery and health and safety performance outputs and this is the same for each of the other performance measures. Therefore comprehensive risk management applied robustly prior to or during manufacturing could enhance business performance for all outputs concurrently.

In conclusion the objective was achieved successfully with the development of a draft architecture capable of generating key risk indicators in the manufacturing sector using Bayesian Belief Network. The next stage in the research project would involve design and development of prototype software capable of managing risks in the manufacturing sector robustly and thereby enhance business performance.

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