OPTIMISATION OF COMPRESSED AIR SYSTEM'S ENERGY USAGE THROUGH DISCRETE EVENT SIMULATION: COMPRESSOR PERFORMANCE

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KEYWORDS

Compressed Air, Discrete Event Simulation, Energy Optimisation, EnergyBlocks, AirBlocks

ABSTRACT

Compressed air systems (CAS) utilised in manufacturing processes require significant energy input for operation. The estimated cost of producing compressed air is considered high with little transparency available when assessing its value in manufacturing. There is currently poor awareness of the performance of CAS in relation to its equipment utilisation and energy optimisation.

This paper presents a modified approach to the EnergyBlocks methodology for representation and simplification of compressed airflow profiles in discrete event simulations (DES). The presented AirBlocks methodology significantly reduces the aggregate data required to represent the dynamic and interdependent nature of CAS. Combining the AirBlocks approach with manufacturing throughput productivity simulations allow a productivity oriented compressed air demand profile to be developed. This offers the capacity to estimate periods of sustained peak, average and minimum air demand, incidents of production stoppages due to air starvation and, identify waste and saving potential in the system. This paper includes an industrial case study where the AirBlocks approach was used in evaluating the performance of an existing CAS. Through simulation - poor compressor utilisation and regular incidents of air starvation were identified as symptoms of insufficient CAS volumetric capacity and an oversized compressor system in an automotive engine manufacturing plant.

INTRODUCTION

It is estimated that global primary energy demand will increase by 40% between 2007 and 2030 with industrial demand projected to grow most rapidly (OECD 2009). During this period industry is expected to account for 20% of the total world energy demand with electrical energy making the largest single contribution. The electrical energy required to meet the demands of CAS in industry accounted for between 10% to 30% of overall industrial energy consumption (Radgen and Blaustein 2001). In 2001 it was estimated that this energy demand required 80TWh of electricity and produced 55 million tonnes of CO2 in the European Union (EU-15) alone (Radgen and Blaustein 2001). Considering between 20-25% of input electrical energy is delivered as usable compressed air energy (Kreith 2000) and 60% or less of air consumed actually make a direct contribution to the product or service which it was intended (Foss 2002), CAS are one of the most expensive in terms of energy utilisation. Figure 1 shows the cost of energy delivery (US$/gigajoule) in comparison to natural gas, steam and electricity.

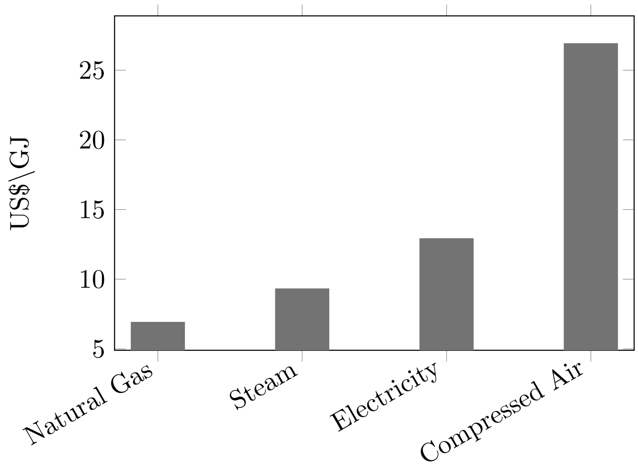

Figure 1: Cost of energy delivery (Yuan et al. 2006)

The energy cost in operating a CAS is undoubtedly high. A compressors average lifespan is 13 and 16 years for 10-110kW and 110-300kW compressors respectively (Radgen and Blaustein 2001). During this time the energy cost will reach up to 78% of the total set up and running cost of the system (Saidur et al. 2010). Figure 2 shows the proportions of cost attributed to each key factor in procuring and operating a CAS.

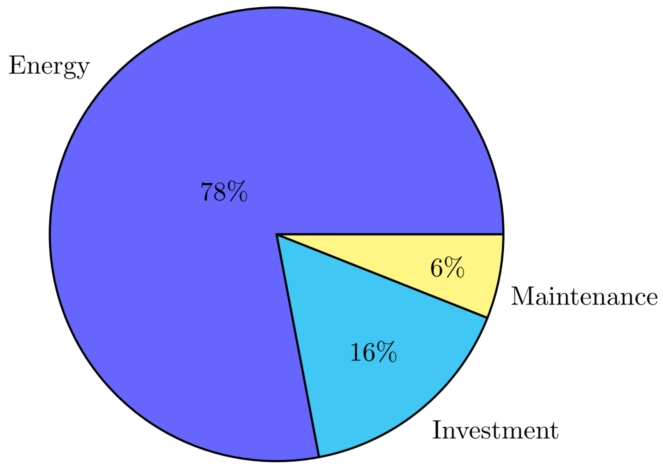

Figure 2: Life time cost of a compressed air system (Saidur et al. 2010)

CAS energy consumption can be further exacerbated through poor practices, poor understanding and the prioritisation of production reliability over system efficiency and energy value. It is reported in literature that compressed air has the perception of being free to the user. Reasoning proposed by McKane and Medaris (2003) suggests that within the manufacturing industry there is a common disconnection between the known presence of compressed air in the distribution network and the associated electrical energy cost required to create this presence. Furthermore, Saidur et al. (2010) states; the only time that issues such as leakage and filter replacement get attention is when air and pressure loss begin to interfere with regular production.

This viewpoint was given additional insight from interviews with 19 European enterprises which found system reliability to be the most important performance criterion as the cost of a CAS breakdown inevitably leads to lost production. Cost was rated as the least important performance criterion for CAS (Radgen and Blaustein 2001). However the emphasis which was placed on reliability was not realised in practice as a report by US Department of Environment (US DOE 2001) found 35% of interviewed end users experienced unscheduled shutdowns with 60% of these shutdowns lasting for 2 days or more.

It is widely recognised in literature that there are vast improvements to be gained in CAS efficiency with much attention given to technical approaches for improving pneumatic component performance, compressor control strategies, systems maintenance, procurement, system and plant design (Saidur et al. 2010). It is however alleged that the implementation of technical measures designed to improve energy efficiencies in the industrial environment are very low (Radgen & Blaustein 2001), a point which has been reiterated by Galitsky and Worrell (2003), Rohdin and Thollander (2006), O'Driscoll and O'Donnell (2012) and Fleiter et al. (2012). Reasons for this lack of uptake are primarily seen as organisational, where a combination of cost accountability and awareness of potential savings are invisible to key decision makers. Failure to highlighting specific performance indicators required to promote energy efficiency in a CAS are largely due to the amalgamation of all electrical energy consumption costs as a single general overhead (Marshall 2013). Furthermore, difficulties in implementing improvements to CAS efficiency can arise from complex management structure within an organisation. Such structures can see responsibility and prioritisation diluted where potential measures for system improvements must pass through different departments with differing functions, e.g. finance, maintenance, procurement (Radgen and Blaustein 2001).

It is estimated that over 50% of industrial plant air systems have potential for large energy saving projects with relatively low project costs US DOE (2001). The perceived lack of focus on implementation measures within the literature, coupled with poor organisational accountability in industry - support the case for the need of a comprehensive data driven approach to improving compressed air systems energy efficiency which targets the decision making process.

The aim of this paper is to present a modified approach to the EnergyBlocks methodology to be used for the refinement and representation of compressed airflow profiles in DES. The presented AirBlocks methodology creates an environment in which a CAS performance can be evaluated with regard to its total manufacturing production demand to identify potential for improving energy utilisation. Evaluation can be carried out on multiple levels of aggregation including individual machine components, single machines, multi-machine operations and a complete manufacturing line. The paper briefly reviews recent and seminal literary contributions which highlight the notable developments in modelling and simulation of energy flows in manufacturing systems.

MODELLING & SIMULATION

The implementation of CAS energy efficiency measures in the manufacturing industry have remained low despite continuous developments on the topic. Current decision mechanisms are largely failing to recognise the substantial technical and economic potential for energy saving. The biggest influencing factor in decision making is that of financial savings. Such decisions must be informed with detailed knowledge of the systems current performance (Talbott 1992). But due to the contextually specific nature of most existing data/information it is difficult to relate it to individual situations faced by CAS users.

Information tools are highlighted by Radgen and Blaustein (2001) as a platform to transcend organisational structural barriers where responsibility for differing aspects of CAS are spread through company departments and levels. Simulation is a modelling tool used to understand system performance and identify potential for improvements (Tako and Robinson 2010). Where an investigation seeks to understand system performance over time and identify potential improvements, simulation can offer the following advantages (Panneerselvam 2006);

- Experimentation times can be compressed.
- Performance can be studied under multiple scenarios.
- Success or failure on a simulated system has no adverse effects on production.

Drawbacks to simulation modelling are the time and cost required to create and verify effective and system comparable models (Wilson et al. 2015).

Thollander et al. (2009) combined energy auditing with production optimisation and simulation as a means to inform strategic investment in a Swedish foundry. Generating performance data which directly correlated to production for assumed future energy cost variations gave decision makers the relevant insight to system performance in the appropriate context to make informed investment decisions.

Maxwell and Rivera (2003) propose the use of a dynamic system simulation to investigate the effects of air pressure on the performance of CAS. The systems approach taken by Maxwell and Rivera (2003) addresses a core element of CAS the interdependent and dynamic relationship between supply and demand. However, the deterministic approach in modelling compressed air demand gives a narrow view of the effects of production variability. This approach does not assess the effect of uncertainty in production such as random occurrences of peak demand and production interruptions. Furthermore the low resolution offered by a fixed 10 second time interval and short (24hr) production period of the demand profile fails to consider the longer term variability in production output and possible instantaneous occurrences of peak air demand.

The integration of production planning and energy performance analysis using DES is a topic which has recently been the focus of some attention. A study by Berglund et al. (2011) highlights the broad separation of plant information systems and production data in manufacturing. The author proposes an integrated approach to handling production and facility energy consumption which evaluates the combined impact of process energy from manufacturing operations and resources, facility energy and building services using DES (Figure 3). While the full range of energy systems proposed by Berglund et al. (2011) is beyond the scope of this study it does highlight the necessity for any developments with respect to DES of CAS to be considered in the context of a more comprehensive approach for integrating energy flow into a production planning environment.

Herrmann et al. (2011) states that dynamic interactions of processes and auxiliary equipment must be considered when planning and controlling manufacturing systems. The author highlights the estimation of time based energy consumption to be of major importance if factory systems are to be considered as a collective. While no single comericially available software yet support such an analysis the author presents three general simulation paradigms which are most commonly pursued for energy oriented manufacturing system simulation (Figure 4).

Herrmann et al. (2011) proposed a generic simulation environment which integrates elements of Paradigm B and C. This approach offers a platform for a comprehensive analysis of energy system performance with respect

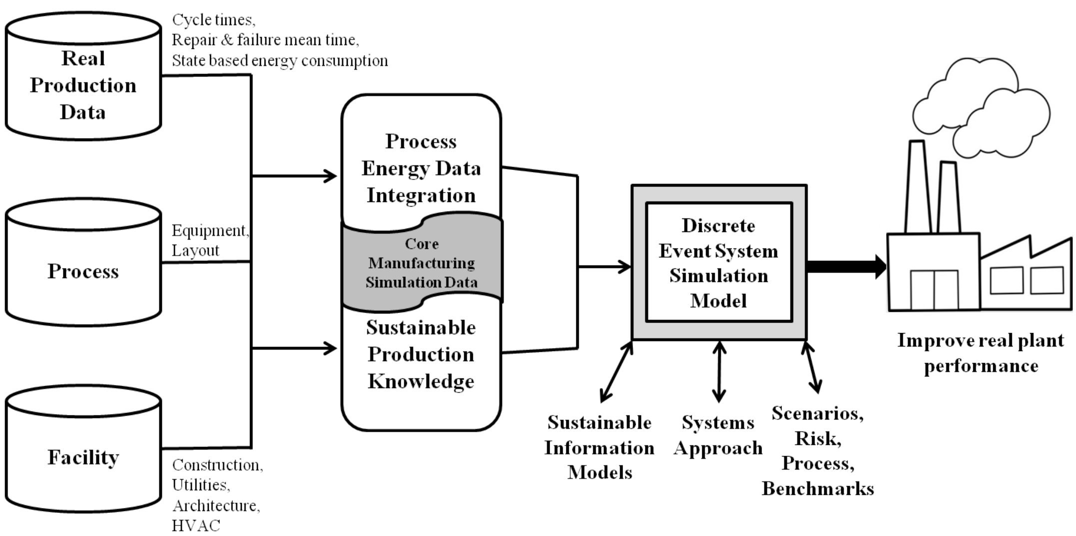

Figure 3: Integration of production & facility energy consumption (Berglund et al. 2011)

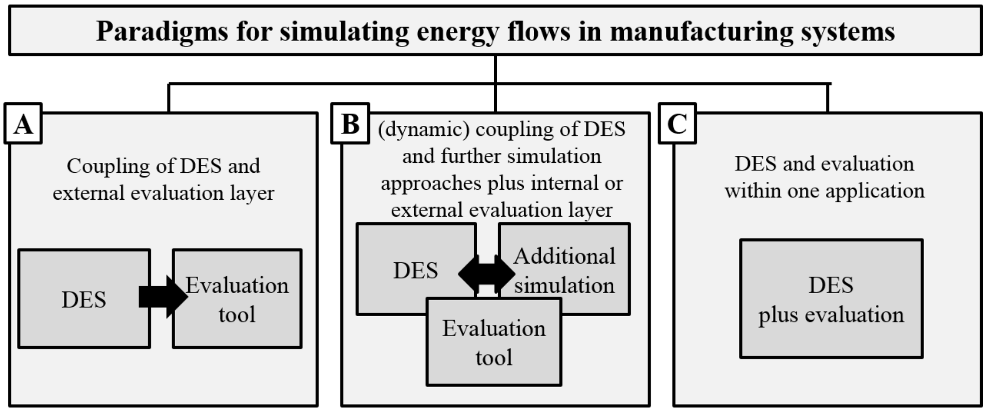

Figure 4: Energy flow simulation paradigms for manufacturing (Herrmann et al. 2011)

to production requirements but is not without drawbacks. The combination of discrete event and discrete time simulation implicitly contains fixed time interval, which if too short will unnecessarily increase demand on computational resources. Subsequent computations may occur where the system remains unchanged offering no benefit, conversely if the time intervals are too large, important events may lack sufficient detail and remain overlooked (Carter and Price 2000).

Discrete event and discrete time simulations have extensive fundamental differences in discretization algorithms, reference locality, sequencing / scheduling and data structures (Nutaro 2007). Modellers would still require a understanding of the differences in simulation type, methods and nature of the model (stochastic & deterministic) (Tako and Robinson 2010).

PROPOSED SOLUTION

Approach

The conservation of mass approach is the adopted method for this study due to its conceptual simplicity and suitability to a fixed volume system analysis with negligible heat transfer. The conservation of mass is described as the time rate of accumulation of mass within a control volume equals the difference between the total rates of mass flow in and out across the boundary (Bejan et al. 1996). As this study is assessing the relation of demand, system capacity (receiver & distribution network volume combined) and supply in an open system the control volume is identified as the CAS capacity with supply and demand dictating the flow of mass across the systems boundaries (Cengel and Boles 2013). The fundamental equations that govern this approach are;

$$\frac{dm_{cv}}{dt} = \sum_i(\dot{m}_i) - \sum_o(\dot{m}_o) \quad (1)$$

where:
$\dot{m}_i$ = input mass flow rate
$\dot{m}_o$ = output mass flow rate
m_{cv} = the total mass contained within the control volume at time t,

To approximate the appropriate system capacity and any occurrences of starvation the mass within the total systems volume at the upper pressure threshold P_1 and the lower pressure threshold P_2 must be determined. Assuming ideal gas behaviour and negligible changes in air temperature, the conservation of mass equation can be expressed as;

$$\frac{(dP_s)}{dt} = \frac{(\dot{m}_i - \dot{m}_o) * R_g * T}{V_{sv}} \quad (2)$$

where:
P_s = the system pressure
R_g = ideal gas constant for air
T = average temperature in the receiver
V_{sv} = combined receiver and network volume.

The required volume of the combined receiver and network volume at the upper pressure threshold and the lower pressure threshold must be equal, thus the volume is approximated as follows;

$$V_{sv} = \frac{m_{mr} * Rg * T}{(P_1 - P_2)} \quad (3)$$

where:
m_{mr} = the maximum mass reduction in a single simulation period.

The combined receiver and network volumes are considered as a single quantity as this allows a balance between network and receiver capacity to be determined during the design process. In order to determine the appropriate compressor output and system capacity using this model, a direct deterministic multivariate optimisation method is employed. This method is referred to as a univariate search where all but one variable is fixed allowing the local optimum value to be found. This variable is in turn fixed and another variable is optimised with the process repeated until there are no further improvements in the objective function (Smith 2016). The resultant data set can be used to approximate the global optimum for the decision making process. When determining the local optimum value the interval halving method is employed as described by Singiresu (2009). The convergence criterion is - the minimum final interval within a tolerance range where there are no occurrences of starvation.

Methodology

The methodology for describing compressed air consumption of production equipment is a modification of the EnergyBlocks planning methodology presented by Weinert et al. (2011). The authors present an approach based on segmenting the power profiles of production equipment in their operating state (see Figure 5).

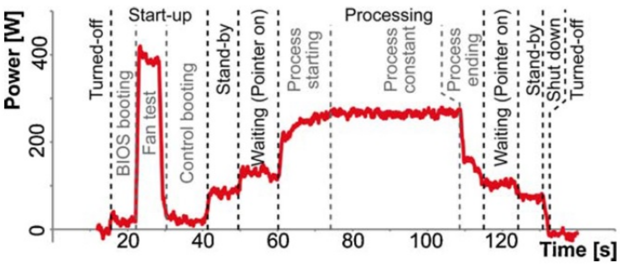

Figure 5: Energyblocks - partition of a power profile (Weinert et al. 2011)

With this approach a production process is modelled as a sequence of EnergyBlocks which represent the whole production process chain. Furthermore a database of EnergyBlocks allow any process chain to be modelled which contains similar process parameters and machine specifications. This approach is modified for the refinement of compressed air profiles for use in DES. Two primary justifications for modifying this process are; (1) a machines compressed air profile may constitute more than one superimposed processes for example, if a machine demonstrated a downstream leakage characteristic when no machining activities are occurring then the logical assumption can be made that the leakage is symptomatic of the machines performance. Thus, any additional air demand processes will result in the consolidation of both contributing factors. (2) The second justification is in reducing the number of interpreted events in the process by defining underlying behaviours, each contributing event can operate concurrently as opposed to sequentially. For the sake of distinction the modified approach is referred to as AirBlocks and a comparative of each approach is made between Figures 6 & 7 using a minimum quality lubrication (MQL) airflow profile for a machine tool.

The AirBlocks approach offers a significant reduction in the datapoints required to represent the same number of processes, the number of events required to represent the cycle is reduced by almost half offering improved computational efficiency in simulation. In addition, underlying

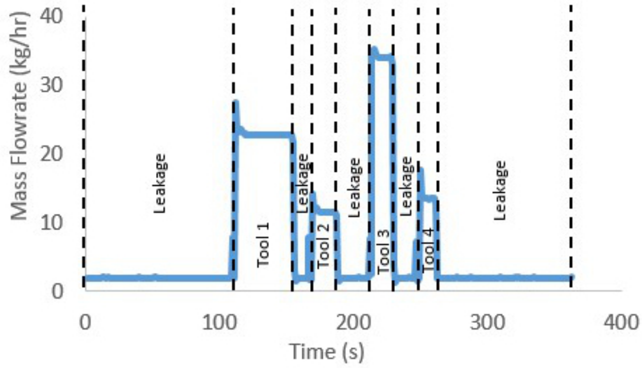

Figure 6: Energyblocks approach

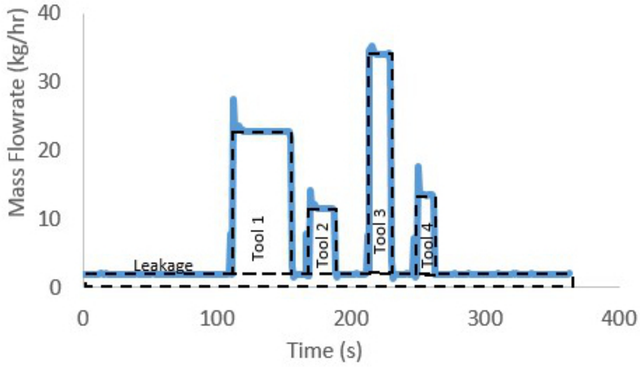

Figure 7: Airblocks approach

contributers such as leakage are more accurately represented allowing greater analysis of any specific individual elements contribution to the production demand.

Simulation

The simulation tools used by the industrial partner for this study are Lanners commercial DES software Witness® linked to bespoke front end within Microsoft® Excel®, further details of which are available in Wilson et al. (2015) & Higgins (2013). This research aims to develop a universally applicable approach to simulating compressed air system performance with regard to its manufacturing production demands a database based method was used to generate and drive CAS performance simulations using DES throughput and productivity data and machine level compressed air demand profiles. This topic has seen development from Randell and Bolmsjo (2001) where a proof of concept for the integration of information between platforms was presented. Interfacing DES software and relational database management systems (RDBMS) is supported by many priority vendors with the most appropriate example presented by Waller (2012). A MySQL RDBMS was selected as the most applicable platform to interface with Witness. This study was limited to an integration of information only although further systems integration is planned.

The basic structure of the database simulator can be categorised as Paradigm B as shown in Figure 4. This structure offers greater functionality where a high level of detail is required when analysing air flows and dynamic interactions between subsystems. Although the level of modelling and simulation complexity is increased and differing model aspects are spread across multiple expert tools, it has been observed that the integration of simulation tools, data storage infrastructure and evaluation tools is necessary to efficiently manage and utilise data generated in a manufacturing environment. Studies carried out by Skoogh and Johansson (2008), Randell and Bolmsjo (2001), Sargent (2003), Weinert et al. (2011), Herrmann and Thiede (2009) and Lind et al. (2009) offer justification and insight to the integration of a database into production, supply chain and energy simulations. A drawback to the multiple platforms required in this simulation approach expressed by Herrmann et al., (2011) is reduced transferability. As this approach is reliant on a fundamental aspect of DES the event set - it could be argued that provided suitable input data can be generated from any alternative DES platforms, this approach is transferable. Furthermore, the selection of RDBMS can increase the platforms transferability if selected appropriately. The simulation structure is presented in Figure 8.

RESULTS & DISCUSSION

The simulation results offered insight into the performance of the existing compressor and capacity arrangement. By comparing simulation results to observed behaviours in the CAS an evaluation of the cause of the incidences of starvation was able to be made.

The existing compressed air supply consisted of approx. 100 m^3/hr (STP Standard Temperature & Pressure) compressors and a total network volumetric capacity of 1.5m^3. Compressor utilisation is approximately 65% (Figure 9) which corresponds with a value of 60% estimated from observation. Charting the existing volumetric capacity against the compressor output shows the initial capacity to be in close proximity to the threshold where occurrences of starvation are likely (Figure 10). Considering the simulation result is derived from a simulated compressor supply with 100% availability, it does not account for the impact a control strategy would have. Thus it is reasonable to assume that the actual threshold for starvation would in reality occur at a marginally increased volumetric capacity but utilisation would be expected to remain the same as it is a function of the compressors output only.

Allowing for the impact of a control strategy, this result was consistent with the behaviour observed in the CAS during operation thus it allowed an informed course of

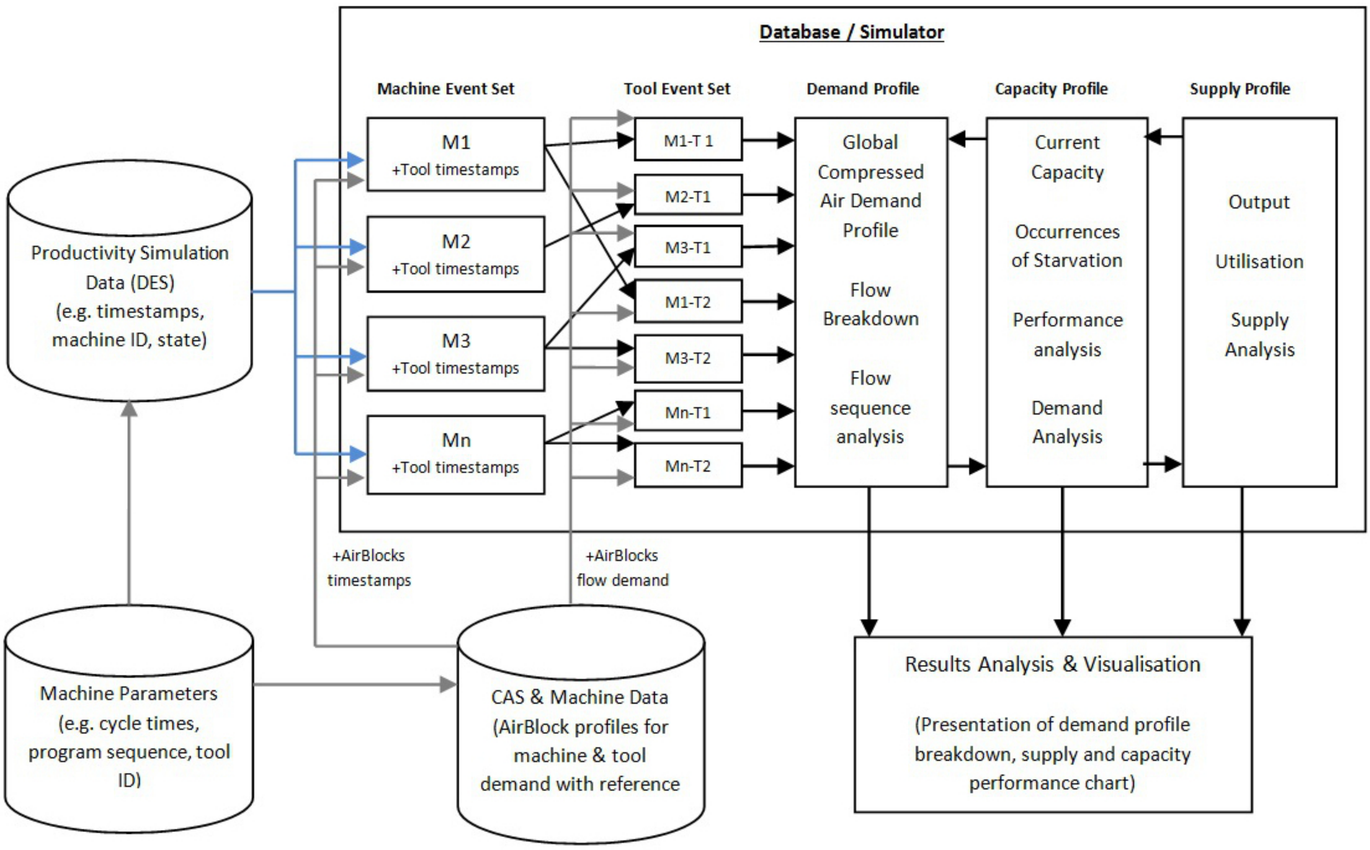

Figure 8: Simulation structure of production oriented CAS simulation

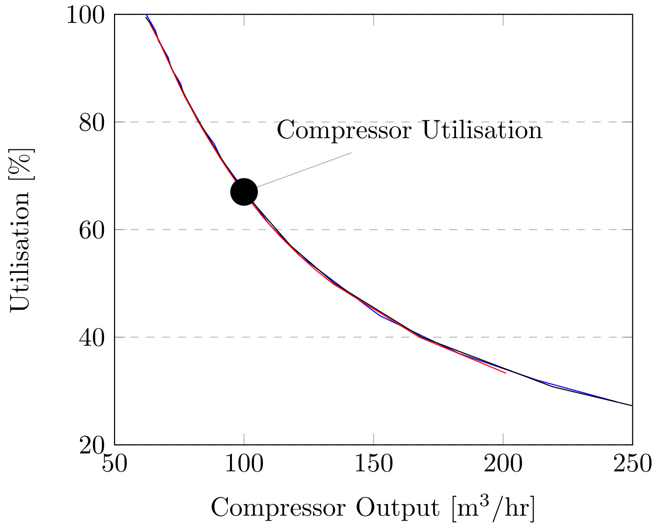

Figure 9: Compressor Utilisation

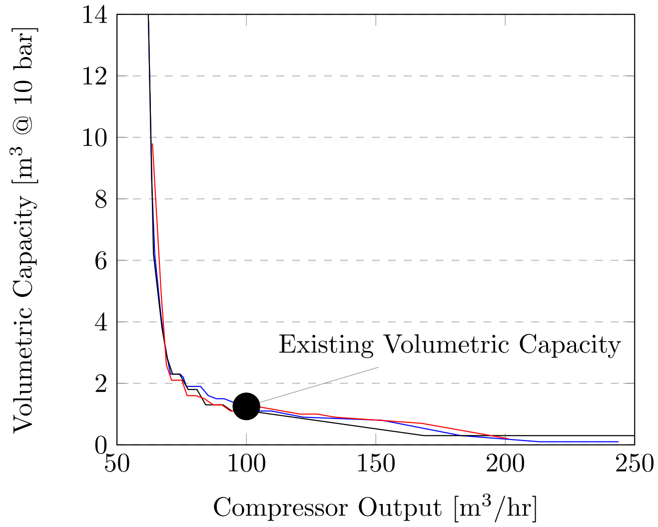

Figure 10: Network Volumetric Capacity / Compressor Output

action to be taken. To overcome the likelihood of further production interruptions due to starvation, the volumetric capacity was increased to 2.5 m^3.

Such insight was not previously available to the industrial partner. Its impact will have long-term positive consequences to the machine availability and therefore productivity seen within the manufacturing facility.

CONCLUSION & OUTLOOK

This paper presented the AirBlocks methodology for representation and simplification of compressed airflow profiles in DES. By combining the AirBlocks approach with manufacturing throughput productivity simulations, a compressed air demand profile was able to be produced which was representative of real world demand on CAS in discrete maunfacturing. This approach allowed the variablity in discrete manufacturing to be accounted for while the reduction in aggregate data enabled long periods of production simulation to be carried out.

The case study presented an application of the AirBlocks methodology as a means of evaluating a CAS by assessing the performance of an air compressor and receiver to a simulated air demand. Within the broader aim of the research study the simulation outcome was aimed to assist decision makers in the design, procurement and implementation process of CAS design and operation. The case study was successful in both its specific aim (compressor performance analysis) and within the broader aim of this study. However the approach is not without weakness. Currently no compressor control strategy was accounted for in the model which would invariably affect the simulation outcome in terms of the starvation threshold and required compressor output. If a control strategy activation range was considered the effect of a narrow activation and deactivation pressure range would increase the required compressor output to meet the demand and the capacity would also be expected to increase. Thus the current simulation results must be considered with a large safety factor.

The novelty aspects of the research are found in the following;

- The simulation method proposed offers a novel approach to simulating a CAS supply, capacity and demand relationships whilst retaining the discrete event simulation paradigm characteristics of event sets and sequential data processing.
- The use of a database simulator builds on previous research by applying it to a CAS data analysis task.
- The AirBlocks method of data simplification is a novel approach to transferring dynamic system data to discrete event data.

Further research in this field will address the impact of a compressor control strategy on a CAS supply system and explore energy reduction measures for CAS.

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