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Air Compressor Mode Identification Using Real-Time Clustering Methods for Efficiency Degradation Detection

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Abstract Insert your abstract here. Include keywords, PACS and mathematical subject classification numbers as needed.

Keywords First keyword · Second keyword · More

1 Introduction

In 2012 industry consumed 2,542 Mtoe of energy globally, which represented over 28% of the 8,980 Mtoe of global final energy consumption IEA (2012). In an Irish context, industry consumed 2.26 Mtoe of energy in 2012, representing almost 22% of Irelands 10.3 Mtoe of final energy consumption. Within the category of industrial energy, compressed air is recognised as an energy intensive utility, accounting for 10% of industrial electricity in the European Union Saidur et al (2010). Energy costs typically account for 78% of the total life cycle cost of a compressed air system Radgen (2006). Compressed air is known colloquially in industry as the fourth fuel, due to the high electrical cost associated with generation. Compressed air systems are typically running at 19% overall system efficiency Saidur et al (2010), due to energy losses largely due to lost heat of generation and leakages.

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2 Determining the operational performance of an air compressor

A wide range of configurations and types of compressed air systems are installed in industry. In many cases there exist systems which are running sub-optimally, either due to unsuitability for the task at hand or running in a faulty condition. Given that compressed air represents such a dense form of energy transport, it is beneficial in terms of long and short term overall energy efficiency goals to manage the performance of air compressors. Performance management is typically achieved through means such as those in Table 1. The key disadvantages of existing methods are either that they are manual and periodic in nature, or that they require the intervention of a human expert in compressed air systems to be effective. In the case of maintenance contracts and periodic audits, there is also the potential for unnecessary work to be carried out, as both these measures are typically carried out on a timescale basis. The intervention of a human expert also lends itself to an inefficient method of performance measurement. An expert may be particularly well versed with one type of system, but not another. The disparate range of compressed air systems can lead to an expert restricting themselves to one type of system, preventing possible lessons learned to be applied in other suitable cases.

In order to analyse a particular compressed air system it is useful to understand how it might relate to other installations. The system analysed in this paper consists of two rotary tooth air compressors with a heated desiccant dryer, with the layout given in Figure 1. These machines are rotary tooth type machines, which are widely deployed across industry for applications with medium pressure and capacity requirements, as shown in Figure 2SEAI (2007) The various types of compressors typically used in industry are shown in Figure 3. Reciprocating and rotary machines are both positive displacement type machines. They work through isola-

Table 1 Existing Compressed Air System Performance Management Methods

Performance Management Method	Advantages	Disadvantages
Maintenance Contracts	Security of asset reliability	Potential for unnecessary work
Periodic Audits	Likely to pick up on common opportunities for improvement	Dependent on skill level of auditor
Sequence Controllers	Can draw on manufacturer knowledge of system operation	Initial configuration may not be maintained due to system changes
BMS Monitoring	Desk-based site wide monitoring capability	Dependent on skill level of BMS reviewer. Unable to pick up on sensor errors

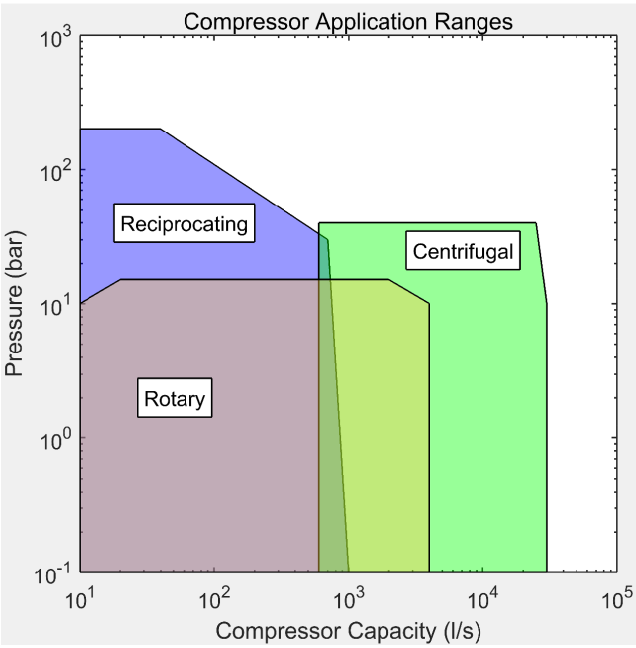

Fig. 2 Compressor Application Suitability

tion of a quantity of air in a space which is then reduced in volume. Centrifugal machines are aerodynamic machines, which operate by imparting kinetic energy to air, which is then converted to pressure energy by stopping the moving air. The three most common types of compressor in industry are rotary, reciprocating and centrifugal machines. The application ranges of these types are shown in Figure 2 SEAI (2007).

Research is being carried out to define the future of compressed air system performance management. In this review the research considered is that of ongoing analysis of compressed air system data. This ongoing analysis could be designated as having any of the goals outlined in Table 2.

Table 2 Goals of Performance Management

Goal	Description	Example Work
Fault Detection and Diagnosis	Monitor system parameters to determine when system is in fault condition and the potential reasons for the identified fault	Using vibration, pressure and current signals to diagnose valve faults for a reciprocating compressor Tran et al (2014)
Prognostics	Monitoring system parameters to determine when a component of a system will no longer perform its intended function Vachtsevanos et al (2006)	Determining the remaining useful life of a gaseous circuit breaker based on gas pressure and ambient temperature Catterson and Costello (2013)
Analytics	Monitoring system parameters to discover meaningful patterns which may advise on potential improvements to system operation	Determining abnormal appliance power consumption based on analysis of individual appliances acoustic noise Pathak et al (2015)
Automated Commissioning	Achieving, verifying and documenting that the performance of a system satisfies the current user requirement	Automatically carrying out the normal testing procedure for an air compressor by replicating the tasks normally carried out during commissioning Mazid and Martin (2008)
Optimisation	Improving system operation or design as measured against some defined criteria	Development of a tool which delivers an optimal design for a compressed air system based on energy and life cycle costing Friden et al (2012)
Control	Managing the operation of a system in order that operating conditions remain in line with design states and undesirable states are avoided	Development of a control algorithm for fixed speed compressors that provides the pressure control capabilities of a variable speed system while limiting energy consumption Facchinetti et al (????)

2.1 Current research into performance management

Figure 4.

Quantitative model based methods are summarised in ...

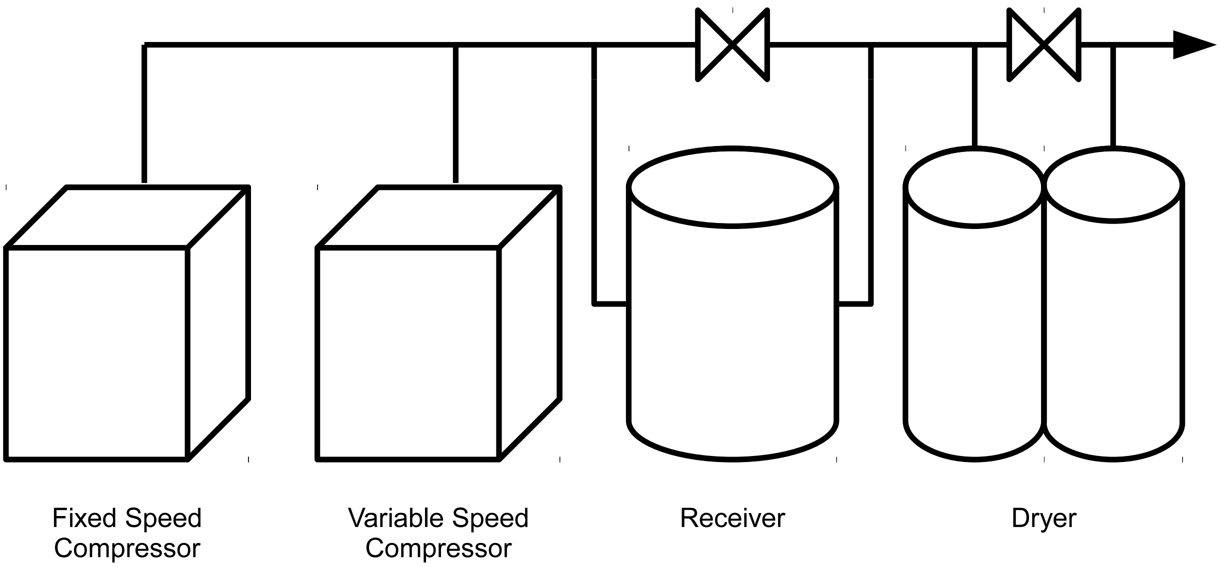

Fig. 1 Test Site Compressed Air System Layout

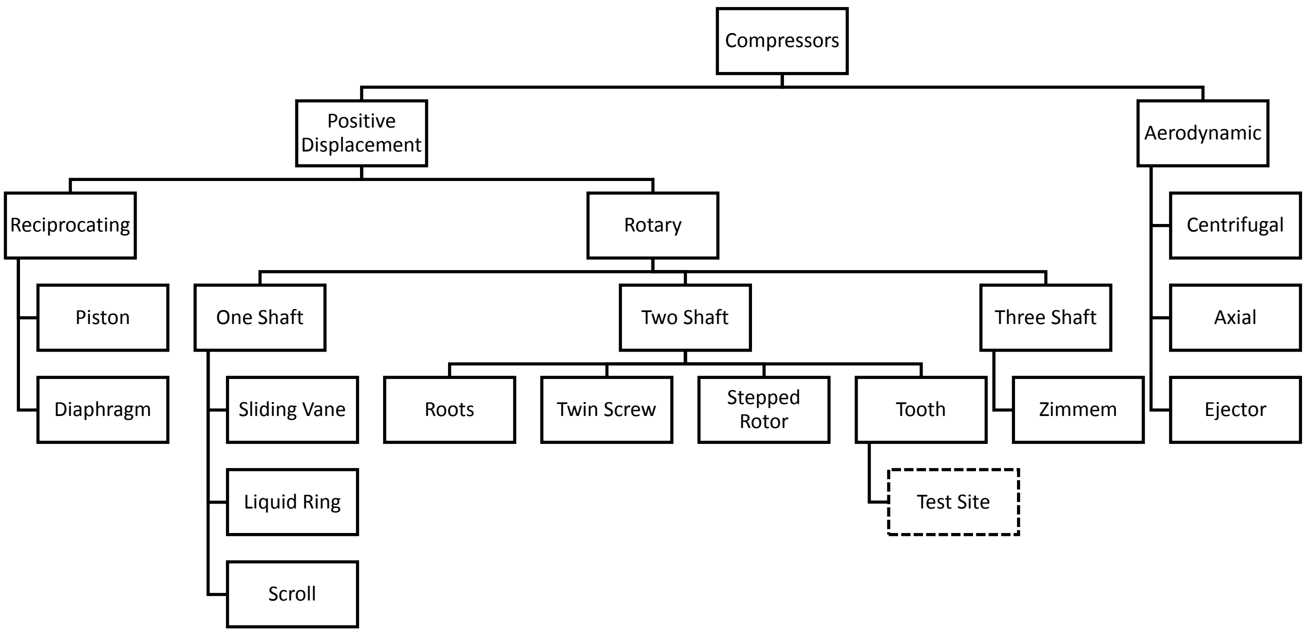

Fig. 3 Compressor Types

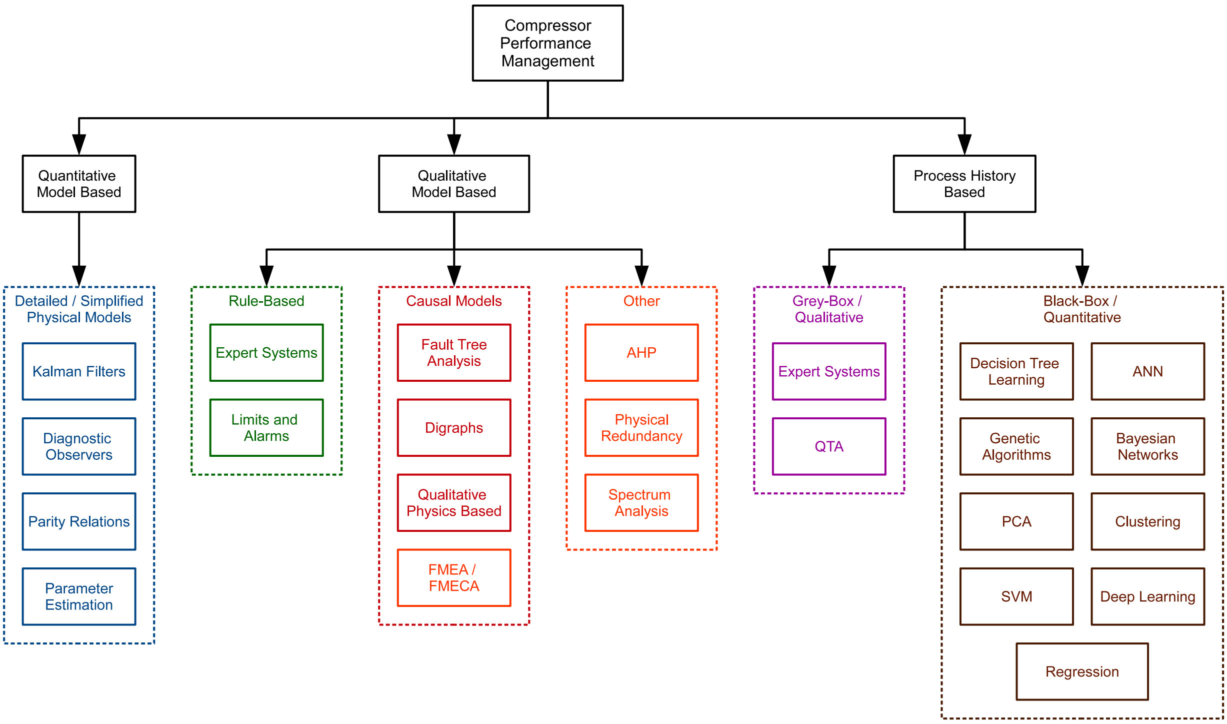

Fig. 4 Current research into performance management methods

Table 3 Quantitative model based methods

Method	Description	Benefits	Disadvantages	Examples
Kalman Filters	A Kalman filter allows the combination of observed and predicted parameters to more accurately predict future parameters than with a physical model alone. It also allows for the reduction of the effects of noisy data on models.	Very accurate Transients may be modelled	Computationally expensive Complex to create Typically require many inputs from system	Surge control for axial compressors Backi et al (2013) Fault detection for gas turbine compressors Salar et al (2010) State estimation of a thermal power plant Nair et al (2011)) Leakage detection of a pneumatic network Krichel and Sawodny (2011)
Diagnostic Observers	Employing state observers, typically one for each fault, which represent a different output from a model, in order that observed differences in outputs may be attributed to faults to how to change a model to remove deviations from expected behaviour	Accurate isolation of individual faults possible	Observers required for each individual potential fault state	Fault detection of a steam boiler feed water preheater Tarantino et al (2000) Estimation of a steam boilers pressure given fuel and feed water conditions Ramezanifar et al (2006) Surge control for axial compressors Backi et al (2013)
Parity Relations	Rearranging and transforming input-output models of a system in order to highlight individual fault conditions	Accurate isolation of individual faults possible	Less effective at identifying multiplicative faults	Fault diagnosis of a wind farm using interval nonlinear parameter-varying parity equations Blesa et al (2014)
Parameter Estimation	Comparison of modelled data, normally using ordinary and partial differential equations, with measured data, with analysis of any residuals to diagnose faults	High level of confidence in modelled data	Detailed physical model required for accuracy	Optimisation of the modelling of a multistage compressor using parameter estimation to determine the surge line Dapeng Niu et al (2011)

Table 4 Qualitative model based methods

Method	Description	Benefits	Disadvantages	Examples
Expert Systems	Using if-then-else rules derived from engineering knowledge of a systems operation to flag when and why a fault is present in operation	Quick deployment potential	Potential that knowledge remains undiscovered/undocumented	Fault diagnosis assistance using IF-THEN rules for an air compressor Liu (2001)
Physical Redundancy	Installing parallel sensors in order that site personnel be notified of an error if sensor values do not match	Simple in concept	Cost and space constraints may limit additional sensor placement	Analysis framework of fault detection schemes based on redundant sensors for aircraft Wheeler et al (2011)
Analytical Hierarchy Process	Decision support for selection of a particular approach, e.g. for maintenance strategy, over another based on pairwise comparisons of suitability toward various goals	Allows documentation of expert decision making in formal manner	Limited real-time performance analysis potential	Maintenance strategy selection for equipment at an oil refinery Bevilacqua and Braglia (2000)
Spectrum Analysis	Analysis of compressor drive and vibrational frequency response to alert when response drifts from normal	Allows for discovery of faults which may be difficult to postulate from first principles	Detailed analysis required for each potential spectrum case	Vibration analysis of reciprocating compressors for valve failure diagnosis Ruilin Lin et al (2010)
Fault Tree Analysis	Postulation of potential areas of failure in equipment	Allows formal documentation of human expert knowledge	Scope of fault detection is as limited as human experts knowledge and expertise	Reliability assessment of an anti-surge control system for a centrifugal compressor Ren et al (2012)
FMEA / FMECA	Analysis of site equipment potential areas of failure and potential effect on other equipment	Critical analysis of most risk-prone areas of a system	Time consuming for development	Compressor safety evaluation model Zhu et al (2013)
Qualitative Physics Based	Derivation of qualitative equations from fundamental physical equations governing system operation to allow for analysis without explicit requirement for numerical values	No requirement for numerically accurate measurement of system variables	Requires initial understanding of physical processes governing system operation	Fault Detection for an AHU Glass et al (1995)
Digraphs	Representation of qualitative models using directed graphs to efficiently incorporate system behaviour for effective analysis	Allows visual representation of qualitative physical equations	Requires considerable domain expertise for creation	FDD for a typical industrial process using SDG for model decomposition Shin et al (2007)
Limits and Alarms	Implementation of user defined limits on key parameters which flag when exceeded or are not met	With correct identification of thresholds can quickly highlight issues with systems	Little diagnosis and isolation potential Correct selection of thresholds dependent on user expertise	Incorporated into modern compressor PLCs

Table 5 – continued from previous page

Method	Description	Benefits	Disadvantages	Examples

Table 5: Process history based methods

Method	Description	Benefits	Disadvantages	Examples
Support Vector Machine / Relevance Vector Machine	A supervised learning technique which when given a sample data set which is labelled according to which class each point belongs in, can determine the optimal plane which splits classes allowing accurate future classification of variables	Can accurately classify non-linear data	Can be computationally expensive in implementation	Compressed air load forecasting for large flows Liu et al (2013); Fault diagnosis for reciprocating air compressor valves Wang et al (2010), Cui et al (2009), Qin et al (2012), James Li and Yu (1995); Fault diagnosis for reciprocating air compressors Verma et al (2011)
PCA	Analysis of a population of variables to determine the population extremes in a given number of directions or components, allowing categorisation of each data point in terms of its position in each direction	Decreased sensitivity of data analysis to noise Reduced dimensionality increases data understanding	Training data must explicitly demonstrate variance in data	Sensor fault detection, diagnosis and estimation for centrifugal chillers Wang and Cui (2005) Fault detection and isolation for a centrifugal compressor Zanoli and Astolfi (2013) Sensor and actuator fault diagnosis for a centrifugal compressor Zanoli et al (2010a)
Artificial Neural Networks	Creation of a network of elements or neurons which may determine output values based on interconnected element's response to external inputs. Networks may be supervised where instances of faulty operation are labelled, allowing the network to generate expected outputs for arbitrary unknown inputs. Networks may also be unsupervised, in which case the topology is adaptively determined based on the inputs.	Can effectively predict non-linear relationships in data	Structure of neural network requires intuitive development	Valve failure detection for reciprocating compressors (Namdeo et al. 2008) Neural network based fault diagnosis of a reciprocating compressor employing genetic algorithms for initial parameter identification Jinru et al (2008)

Table 5 – continued from previous page

Method	Description	Benefits	Disadvantages	Examples
				Performance prediction of a centrifugal air compressor employing artificial neural networks and genetic algorithms Luo Fangqiong and Huang Shengzhong (2011) Generation of a gas generators compressor performance characteristic map Ghorbanian and Gholamrezaei (2009) Yu et al (2007)
Genetic Algorithms	Determining the optimum point a system can operate at, by selecting random members of a population of samples and using them as parents of successive samples, which tend toward the optimal sample	Easily transferred to existing simulations and models	No assurance that optimal application will indeed be the global optimum	Noise minimisation of a hermetic compressor Dasilva (2004) Neural network based fault diagnosis of a reciprocating compressor employing genetic algorithms for initial parameter identification Jinru et al (2008) Performance prediction of a centrifugal air compressor employing artificial neural networks and genetic algorithms Luo Fangqiong and Huang Shengzhong (2011) Parameter identification for a centrifugal compressor model Xiaogang et al (2013)
Decision Tree Learning	Automatic classification of output variables by organising data into subsets, generating rules in a tree like structure	Require reasonably low data preparation effort	Highly unstable when perturbations in training data are present	Fault diagnosis for a modular production system Demetgul (2013)

Table 5 – continued from previous page

Method	Description	Benefits	Disadvantages	Examples
Deep Belief Networks	Stacked Restricted Boltzmann Machines (RBMs), which are themselves simple unsupervised neural networks	Allow more complex understanding of data relationships than with lower level machine learning techniques	Complex to initially understand structure	Reciprocating compressor valve fault diagnosis Tran et al (2014)
Clustering	Grouping data readings into different groups where intragroup similarity is greater than intergroup similarity	Relatively simple to deploy	Some qualitative assessment for optimal number of clusters may be required	Fault detection and isolation for a centrifugal compressor based on PCA and Clustering Zanoli et al (2010b) Adaptive clustering for pneumatic system fault detection Petković et al (2012)
Bayesian Networks	Creation by learning or using prior knowledge of graphical probabilistic models which give relationships between variables	Can provide an excellent interpolation to real world simulations	Calculation of parameters for Bayesian models can be initially difficult	Fault diagnosis of a pneumatic air braking system Lingling (2010) Fault detection via classification of compressor variables compressed dimensionally via PCA Liu and Chen (2009)
Regression Modelling	Statistical estimation of the relationship between two or more variables	Reasonably low effort required for deployment with concept simple to understand	Requires strongly defined relationships between variables to be of any use	Optimisation of a network of compressors in parallel Kopanos et al (2015)

Table 6 Please write your table caption here

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3 Rule base development and testing

4 Operational mode identification

5 Fault detection effectiveness

6 Conclusions and future work

7 Background: Air Compressor Operational Concerns

8 Variable Speed Compressor Operational Modes

9 Clustering for Mode Identification

10 Real-Time Analysis Implementation

11 Results

12 Discussion

13 Conclusions

14 Section title

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15 Section X

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15.1 Subsection title

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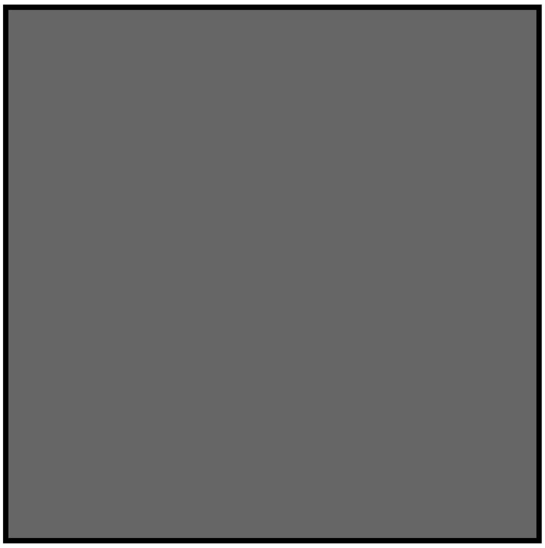

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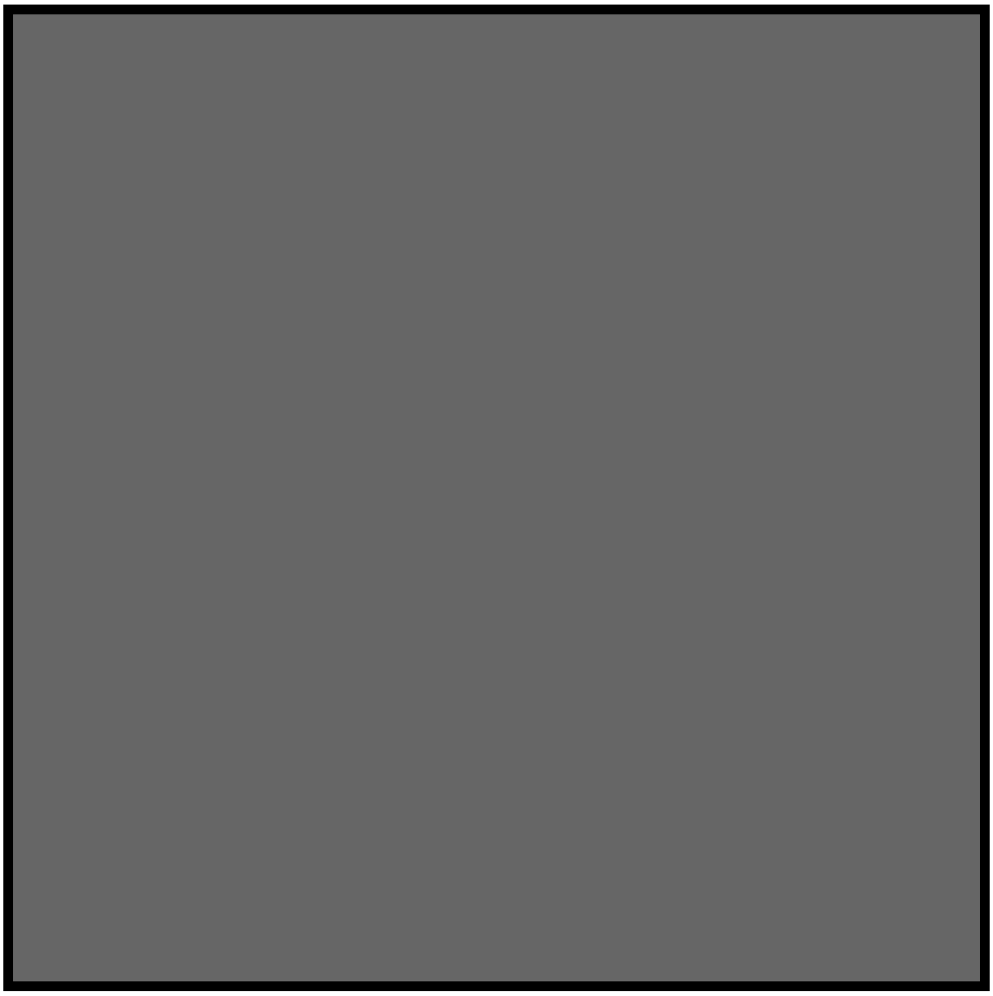

Fig. 6 Please write your figure caption here

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