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SUMMARY

Introduction

The University of Dundee in association with Whole Life Consultants Ltd has been commissioned by the Construction Scotland Innovation Centre (CSIC) on behalf of the AIMCH partners to undertake a wide-ranging literature research analysis and compile a report focused on construction productivity measurement studies and protocols.

The AIMCH project aims to help tackle the UK housing crisis by using industrialised offsite solutions to deliver high quality homes faster, more reliably and at the same cost as masonry-built homes.

The aim of the literature review is to help the AIMCH partners to understand the current landscape of productivity metrics and future trends, and to enable them to gain a good understanding of key tools and techniques in all areas of monitoring. The outputs will be used to inform and influence the way in which the partners choose to measure their on-site activities.

The principal metrics considered are:

1. Safety
2. Productivity including labour productivity
3. Quality including rework, defects and reliability
4. Cost including cost/m^2, cost per unit, cost effectiveness
5. Time including duration (normalised to take account of differences in design) and percentage of milestones achieved (including planned completion dates)
6. Predictability of time and cost
7. Efficiency
8. Material waste

In addition, a section on emerging technologies has been included in Appendix F and a review of the studies to which reference is made in the Academic Brief is provided in Appendix G.

Whilst the importance of life cycle costs and sustainability, particularly carbon emissions, is recognised, the lack of data militates against consideration of the former, whilst the partners intend to give separate consideration to the latter.

To ensure clarity and avoid ambiguity, an agreed Glossary of Terms is provided in Appendix C and a list of criteria against which each performance metric should be assessed is shown in Appendix D.

The report starts by providing guidance on the choice of metrics, on leading and lagging indicators, on the appropriate level of detail and on the level of alignment with suggestions provided by industry and government bodies such as the Construction Leadership Council. This is followed by a section dedicated to each of the principal metrics. Each section is structured as follows.

- Preamble of general remarks.
- List of each performance metric considered.
- Description of each recommended metric and method of measurement together with an assessment of its merits and disadvantages, and details on the level of uptake and/or examples where it has been used.
- Summary of the relative merits in the opinion of the research team of each metric in that section. Members of the consortium may well take differing views.
- Recommendation as to which metric should be considered for use in which circumstances with accompanying rationale.

A full review and assessment of the metrics which are not recommended for use in the AIMCH project is provided in Appendix E.

The report concludes with recommendations as to how the outputs might best be used.

Relevant references are cited throughout, and a bibliography of other references that have been identified but not cited is also provided.

Safety

The following metrics were reviewed.

Leading

- Number of safety observations (over a given period)
- Percentage of negative randomly performed drug and alcohol tests
- Number of times work has been stopped due to safety breaches
- Percentage of audited items in compliance
- Percentage of tasks which are planned in advanced
- Percentage of orientation events attended by the owner's project manager

Lagging

- Incidence rates
- Frequency rates
- Severity rate

Based on our review of the literature, we recommend the use of two leading metrics: percentage of audited items in compliance and percentage of tasks which are pre-planned. We also recommend the use of one lagging metric: frequency rates, and in particular, number of days of lost work per 100,000 hours worked.

We further recommend that consideration should be given to supplementing this metric with the number of near misses recorded per 100,000 hours worked.

Productivity

The following metrics were reviewed.

- Gross value added/number of jobs
- Gross value added/total hours worked
- Gross value added/labour cost
- Value of work completed/total hours worked
- Value of work completed/labour cost
- Labour hours per plot
- Output of physical units/total hours paid
- Output of physical units/available hours worked
- Output of physical units/productive hours worked
- Delays
- Earned value/Actual cost
- Earned hours/Actual hours
- Construction Industry Institute Construction Performance Assessment

Where different methods of measurement were possible, these were also reviewed.

Our recommendations are as follows.

If detailed information about the process of construction, its context and constraints is required, and if the labour force cannot be used to keep the necessary records, then direct, continuous observation by a trained observer should be used.

If the purpose is simply to determine the reduction in labour inputs occasioned by off-site manufacture, then the use of RFID or BLE should be piloted after suitable investigation of any constraints or shortcomings that might arise. In any case, it would be advantageous, not only to the AIMCH project but to the whole industry if RFID were supplemented by direct observations and activity sampling so the relative merits of each approach could be determined in more depth.

Quality

The following metrics were reviewed.

- HBF star rating
- Field Rework Index
- ISO 9001 Accreditation
- Yield (ratio of number of non-defective items to total number of items manufactured)
- Quality rating ($\frac{Total\ construction\ capital\ cost - Cost\ of\ post\ occupation\ defects}{Total\ construction\ capital\ cost}$)
- Costs due to error/total construction cost
- Number of reportable items
- Number and type of items that did not pass visual inspection

For Barratt, and L&Q, the HBF star rating and the number of reportable items are widely recognised, objective, mature, relate closely to strategic objectives and areeasily administered so we recommend that their use should be continued. For similar reasons, and because its use is suggested by CLC, we recommend that the NHBC Quality rating should also be used by Barratt and L&Q. In addition, we recommend that Forster Roofing should continue to use the number of reportable items as a measure of quality.

Cost

From the outset, it is important to define what is meant by cost. We need to be clear whether we mean initial (capital) costs (including site preparation costs, professional fees and construction costs) or life cycle costs (site acquisition + capital costs + renewal + operation + maintenance + end of life cost). Although the importance of the latter has been recognised, it was agreed that for the purposes of this report cost should be taken to mean the construction cost of a house, since one of the current aim of the AIMCH project is to compare the construction costs of houses built conventionally (brick and block construction) with houses built offsite to varying degrees.

The following metrics were reviewed.

- Average construction cost/m^2 (GIFA)
- Construction cost/bedroom
- Average construction cost/plot
- Construction cost/item or element
- Cost variance
- Change in cost of construction
- Cost of rectifying defects
- Prelims cost/capital cost
- Cost growth (%)
- Phase cost ratio
- citiBLOC/m^2 (a citiBLOC is the average price of a basket of '*representative construction items'*)

To satisfy the principal strategic objective for Barratt and L&Q, we recommend that the metrics used should be the average construction cost per plot and the average cost of rectification of defects per plot. Costs should exclude the costs of foundations, which are assumed to be the same for conventional and OSM, but should include the costs of prelims which may vary between conventional and off-site construction. The costs of solutions using off-site manufacture should include the costs of investment in the necessary facilities, design of bespoke solutions, manufacturing, logistics and assembly. Clearly, costs will have to be compared on plots of similar characteristics in terms of quality and functional specification eg two bedroom terraced social housing.

To compare the costs of individual elements (eg walls roofs, etc.), it will be necessary to collect construction costs related solely to those elements. Of these, the most difficult will be labour hours and preliminaries (eg additional cranage or reduction in use of forklift to deliver materials). To accomplish this, it may well be necessary to carry out direct observations.

Time

The following metrics were reviewed.

- Overall time (or programme duration)
- Time/output of physical units
- Time per plot
- Time/m^2
- Delivery speed
- Change in time for construction
- Projects schedule variation (%)
- Schedule growth (%)
- Project schedule factor ($\frac{Actual\ total\ project\ duration}{Initial\ predicted\ project\ duration + Duration\ of\ approved\ changes}$)

In satisfying the principal strategic objectives of Barratt and L&Q, the average elapsed construction time per plot is the metric of interest, since this defines when a house will be ready for the customer. Moreover, this metric can be easily converted in the elapsed time per m^2 whose use has been suggested by CLC (see Section E.5.2 for more details on the use of this metric). As with costs, times will have to be compared on plots of similar characteristics in terms of quality and functional specification. Additionally, because urgency is driven by demand, it will be necessary to ensure that that build contexts are comparable too if comparisons between on-site and off-site construction are to be meaningful. To achieve this, it may be necessary to compare both average and minimum construction times. Again, we recommend that the time to construct foundations is excluded since these will be more or less the same for on- and off-site construction. For off-site construction, consideration will have to be given to any time required for bespoke design, for manufacture, and for transportation as well as assembly on site. We recommend that the time taken for each of these phases is recorded.

For Stewart Milne and Forster Roofing, the time required to construct the relevant elements is the focus of attention. It will therefore be necessary to record the start and completion times of each relevant activity. This may be achieved by the operatives themselves, by supervisors or by intermittent or continuous observations by an independent observer.

Predictability

The following metrics were reviewed.

- Time predictability – change in completion date
- Time predictability – average percentage overrun
- Cost predictability – average percentage overrun
- Cost and time predictability – SmartSite KPIs
- Safety, productivity, quality and material waste predictability

In the light of the AIMCH partners' strategic objectives, and in the pursuit of simplicity and consistency we recommend that time and cost predictability should both be measured in terms of the average percentage overrun. For complete houses, it should be measured at the plot level (ie average percentage overrun per plot). It can however be measured in the same way for any element or activity in the construction process eg walls, floors or roofs.

Efficiency

Efficiency was defined as doing more with less. A process is efficient if waste is minimised ie if maximum output is produced by a minimum of resource. The many ways of measuring waste wherever it occurs in the process are best expressed in the context of lean thinking. Since these are generally only partial measures of efficiency in terms of our definition, we conclude that there is no unique, comprehensive and generally accepted metric describing efficiency. We therefore suggest that metrics describing wastage in labour, plant, material and finance are developed on a case by case basis taking inspiration from sectors such as manufacturing where, for example, the efficiency of a plant is often described by the so called "down time". When no other viable option is available, we suggest the adoption of percentage margin as an umbrella metric for efficiency whilst recognising that it is also a measure of 'efficiency' of the whole process including for instance sales and marketing.

Material waste

The following metrics were reviewed.

- Volume of waste/100m^2
- Weight of waste/100m^2
- Volume of waste/£100k
- Weight of waste/£100k
- Percentage of segregated material waste
- Amount of material waste to landfill
- Amount of material diverted from landfill
- Percentage waste
- Net waste
- Tonnes/£m revenue

In our view, the most relevant metric is the net waste measured as the difference between the 'value of materials not incorporated in the construction works' and the 'value of additional recovered materials incorporated in the construction works or in off-site applications'. If the intention is to eliminate waste entirely in the recognition that recycling and re-use have costs associated with them, this metric is directly relevant. At the same time, it can be used for particular types of materials, for particular elements of construction, for complete projects or across the whole company. We are conscious that this is not the method currently preferred by the partners, but would like to test the appetite for using it in conjunction with the current metrics

Overall conclusions and recommendations

The choice of metric is critically dependent on the strategic objectives. Since different AIMCH partners have different objectives, it is unlikely that a single set of metrics will satisfy all partners. Nevertheless, the results of the literature review and analysis we have undertaken provide comprehensive evidence on which to base decisions about which metric should be used in which circumstance.

We recommend that each partner carefully reviews the recommendations we have made together with the underlying rationale, and checks that the metrics proposed satisfy both their strategic objectives and any internal constraints that may apply.

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1. INTRODUCTION

1.1. BACKGROUND

The University of Dundee in association with Whole Life Consultants Ltd has been commissioned by the Construction Scotland Innovation Centre (CSIC) on behalf of the AIMCH partners to undertake a wide-ranging literature research analysis and compile a report focused on construction productivity measurement studies and protocols. The literature review is to cover site and factory measurement studies across a range of sectors and countries, focusing on construction whilst exploring other industries.

1.2. AIMS AND OBJECTIVES

The AIMCH project aims to help tackle the UK housing crisis by using industrialised offsite solutions to deliver high quality homes faster, more reliably and at the same cost as masonry-built homes.

The aim of the literature review is to help the AIMCH partners to understand the current landscape of productivity metrics and future trends, and to enable them to gain a good understanding of key tools and techniques in all areas of monitoring. The outputs will be used to inform and influence the way in which the partners choose to measure their on-site activities.

Specifically, the objectives are:

- to produce a research report on previous construction productivity measurement studies covering productivity, quality, cost and efficiency, identify gaps and monitoring protocols;
- to examine different methods of measuring productivity with examples to determine what has worked well and why; and
- to prepare recommendations to inform future AIMCH measurement studies.

At a meeting of the project steering group on 25 April 2019, it was agreed that the principal metrics to be considered should be expanded to include the following.

1. Safety
2. Productivity including labour productivity
3. Quality including rework, defects and reliability
4. Cost including cost/m^2, cost per unit, cost effectiveness
5. Time including duration (normalised to take account of differences in design) percentage of milestones achieved (including planned completion dates) achieved
6. Predictability of time and cost
7. Efficiency
8. Material waste

Whilst the importance of life cycle costs and sustainability, particularly carbon emissions, was recognised, the lack of data militates against consideration of the former, whilst the partners intend to give separate consideration to the latter.

A full review and assessment of the metrics which are recommended for use in the AIMCH project is provided in Section 3. Similar information for the metrics which are not recommended are provided in Appendix E.

In addition, a section on emerging technologies has been included in Appendix F and a review of the studies to which reference is made in the Academic Brief is provided in Appendix G.

To ensure clarity and avoid ambiguity, an agreed Glossary of Terms is provided in Appendix C and a list of criteria against which each performance metric should be assessed is shown in Appendix D.

Following this introduction, we set out some general principles relating to performance metrics before showing the findings of the literature review for each performance metric in turn. Each section is structured as follows.

- Preamble of general remarks.
- List of each performance metric considered.
- Description of each recommended metric and method of measurement together with an assessment of its merits and disadvantages.
- Summary of the relative merits in the opinion of the research team of each metric in that section. Members of the consortium may well take differing views.
- Recommendation as to which metric should be considered for use in which circumstances with accompanying rationale.

The report concludes by collating the relative merits of each metric and the recommendations for use.

2. GENERAL PRINCIPLES

2.1. CHOICE OF METRIC

Performance metrics must be chosen with the utmost care. Their purpose is ultimately to change behaviour, but it is all too easy to choose metrics that promote unintended or sub-optimal behaviours. For example, if a supervisor is to be judged on the number of person hours required to build a house, there is a danger that quality will suffer as a result unless mitigating measures are put in place.

The general principle is that metrics should relate to strategic objectives, and that subsystems should not be optimised at the expense of the overall system. It may be necessary for a sub-system to be sub-optimal in order to optimise the overall system. For example, it may cost more to increase the quality of build, but the resulting increase in value may more than offset the increase in cost.

2.2. LEADING AND LAGGING METRICS

It is also necessary to distinguish between leading and lagging metrics. Leading metrics focus on the future, on trends and on preventative measures. For example, the proportion of operatives wearing safety helmets may be a good predictor of the number and severity of head injuries actually suffered. Lagging metrics record what has been achieved, and are generally used to determine whether strategic and operational objectives have been met. A good metric will have a diagnostic capability that allows the user to determine the cause of any deviation from the desired outcome.

2.3. LEVEL OF DETAIL

The level of detail is of paramount importance. In general, high level metrics are easier to measure but do not yield as much useful information as lower level metrics. However, increasing granularity of measurement invariably costs more than overview measures. For example, it costs less to collect the number of person hours required to build a house than the number of person hours to build each element of the house.

2.4. ALIGNMENT WITH METRICS IN USE OR RECOMMENDATIONS

The choice of metric is critically dependent on the strategic objectives. Since different AIMCH partners have different objectives, it is unlikely that a single set of metrics will satisfy all partners. Whenever the partners' strategic objective includes comparing their performance with that of other organisations, the possibility of adopting the most, commonly accepted and widely used metrics – at the expenses of metrics that would provide a more accurate representation of their performance – should be considered.

Although the principal purpose of this literature review is to inform AIMCH partners' measurements in subsequent work packages, to facilitate this comparison process, recommendations resulting from this literature review have been aligned as far as possible, with the recommendation provided by the Construction Leadership Council (CLC) in the recently published *Innovation In Buildings Workstream. Housing Industry Metrics* report[1].

[1] CLC, 2018. *Innovation in building workstream. Housing industry metrics*. Available at: http://www.constructionleadershipcouncil.co.uk/building-metrics/ (Accessed: 27/05/2019).

3. FINDINGS OF THE LITERATURE REVIEW

3.1. SAFETY

3.1.1 Preamble

Accidents happen so infrequently that they can only be used at the highest level as a performance metric. They certainly cannot be used meaningfully below project level, and even then, only for very large projects. Most usually, they are expressed either at company, regional or national level. For this reason, in the field of safety it makes more sense to use leading rather than lagging measures of performance. Research in the oil and gas sector[2] suggests that leading indicators can be used to correctly predict the future safety performance of a company. So in this section, leading are followed by lagging metrics.

The leading metrics we have identified are: number of safety observations per worked hours, percentage of randomly performed drug and alcohol tests, number of times work stops due to safety breaches, percentage of audited items, percentage of audited items which were found to be compliant, percentage of pre-planned tasks, and percentage of orientations events in which the owner has been an active participant. The number of near misses may be interpreted as either a leading or lagging indicator

The lagging metrics we have identified can be grouped in two sub-categories, depending on the quantity used to normalise the recorded events: those indicators which are expressed as a ratio between the number of recorded events (in a given time) and the total number of employees, and those which are expressed as a ratio between the number of recorded events (in a given time) and the number of hours worked. Based on HSE3 definitions, the former are termed Incidence rates, the latter frequency rates. The severity of accidents can also be categorised as a lagging metric.

We identified the following leading safety metrics:

- Number of safety observations (over a given period)
- Percentage of negative randomly performed drug and alcohol tests
- Number of times work has been stopped due to safety breaches
- Percentage of audited items in compliance
- Percentage of tasks which are planned in advanced
- Percentage of orientation events attended by the owner's project manager;

and the following lagging metrics

- Incidence rates
- Frequency rates
- Severity rate.

Details of the metrics whose use we recommend are provided below: details of the remaining metrics are provided in Appendix E.1.

[2] Salas, R. and Hallowell, M., 2016. Predictive validity of safety leading indicators: Empirical assessment in the oil and gas sector. *Journal of Construction Engineering and Management*, *142*(10), p.04016052.

[3] HSE, 2015. *Injury frequency rates*. Available at: http://www.hse.gov.uk/statistics/adhoc-analysis/injury-frequency-rates.pdf (Accessed: 08/05/2019).

3.1.2 Percentage of audited items in compliance

Percentage of audited items in compliance	
Method of measurement	Requires the development of a set of procedures, list of items or activities to be audited. Observations are taken at random intervals and non-compliances recorded.
Merits	• Relates to strategic objectives. • Simple, easy to understand, objective, reliable and verifiable. • Changes in this metric allow evaluation of the timeliness of the safety system and, specifically, how quickly corrective measures are implemented.
Disadvantages	• Constant use of resources to collect, update and analyse data.
Use	• Reference to this metric can be found in research papers[4,5]. Used by some contractors.

3.1.3 Percentage of tasks which are pre-planned

Percentage of pre-tasks which are planned ahead of a task	
Method of measurement	A detailed list of all the tasks connected to a job is required. Pre-task planning forms/checklists or 'Risk Assessment Methods', have to be prepared, circulated and filled out by contractors and/or sub-contractors for each of the scheduled task. Pre-task planning checklists should include, but not be limited to details of the project type and contract under which the job is carried out, the required PPEs, safety works practices and list of hazardous materials[6]. They can be considered a generalised and simplified version of the assessment checklists proposed by HSE for lifting and carrying[7]. Filled pre-task planning forms are discussed on a daily basis with workers directly involved in the completion of the job to raise awareness of the associated risks[8].
Merits	• Simple, easy to understand, objective, cost effective, verifiable, and has some relationship to strategic objectives. • Implies a direct involvement of sub-contractors and the workforce. • As all the practices involving planning, it allows the avoidance of delays and forces people to think about the actual task/activity that has to be carried out. • Digital tools to produce and fill pre-task checklists are available[9].
Disadvantages	• Not directly related to strategic objectives. • Tasks might have to be defined at a higher level of detail compared to the case of traditional risk assessment programs. • To be effective it requires a daily involvement of the workforce.
Use	• Widely adopted among construction companies in UK and US[10].

[4] Liu, H., Jazayeri, E. and Dadi, G.B., 2017. Establishing the influence of owner practices on construction safety in an operational excellence model. *Journal of Construction Engineering and Management*, 143(6), p.04017005.

[5] Duff, A.R., Robertson, I.T., Phillips, R.A. and Cooper, M.D., 1994. Improving safety by the modification of behaviour. *Construction Management and Economics, 12(1),* pp.67-78.

[6] https://info.wellworkforce.com/hubfs/Pre-Task%20Plan-Checklist.pdf (Accessed: 16/05/2019).

[7] http://www.hse.gov.uk/pubns/ck5.pdf (Accessed: 16/05/2019).

[8] Jazayeri, E. and Dadi, G.B., 2017. Construction safety management systems and methods of safety performance measurement: A review. *Journal of Safety Engineering, 6(2),* pp.15-28

[9] https://www.gocanvas.com/mobile-forms-apps/21548-construction-pre-task-planning-ptp- (Accessed: 16/05/2019).

[10] http://www.hoffmancorp.com/wp-content/uploads/2013/11/Pre_Task_Plan_2010_10.pdf (Accessed: 16/05/2019).

3.1.4 Frequency rates

Frequency rates	
Method of measurement	Frequency rates are lagging indicators describing the lack of safety in terms of number of events (whether they are accidents, near-misses or days of lost work) in a given number of hours worked over a period (usually one year). Frequency rates are metrics commonly used across industries and sectors. Differences in the number of hours worked used for the normalisation can be found in the literature. Variations exist both between countries and within countries themselves. In USA frequency rates are expressed per 200,000 hours worked. In the UK, although frequency rate metrics are usually expressed per 1,000,000 hours worked, cases in which the number of recorded events is normalised by 100,000 hours worked can be found[11]. The Major or Specified injuries Frequency Rate and the Over-7-day Injuries Frequency Rate defined by the Health and Safety Executive[12] (HSE) are examples of frequency rates describing the number of reported injuries per 1,000,000 hours worked. Further incidence rates can be obtained opportunely by normalizing against a variety of parameters chosen based on the purpose of the measurement. The following is a list of some of the lagging indicators that can be used for producing alternative frequency incidence rates. • Number of days since last accident • Total number of accidents and incidents (fatal and nonfatal); • Number of first aid injuries; • Number of incidents that led to one or more lost days; • Number of incidents that led to seven or more lost days; • Total number of near misses; • Total number of days lost due to injury or work-related illnesses; and • Number of overdue action items over a given period (eg 6 or 12 months). Some of the more commonly used frequency rates metrics are: • Total recordable injury rate (TRIR), which is based on the total number of reportable injuries; • Lost Time Cases (LTC), which is based on number of cases that resulted in the employee being unable to work in the assigned work shift; • Days Away, Restricted or job Transfer (DART), which is based on the number of incidents that led to one or more lost days, one or more restricted days, or days that an employee was transferred to different tasks within a company. This metric is widely adopted in USA; • The Lost Time Injury Rate (LTIR), which is the UK version of the American DART (see above) and which is based on *"all lost time injuries and injuries that result in restricted duty or transfers"*[13]; • Accident Frequency Rate (AFR), which is based on the number of reportable accidents. • High Potential Incident rate (HiPo), which is based on the number of incidents and near misses that could have resulted in serious injuries or fatalities. Resources required to correctly capture these lagging indicators are those mentioned in Section E.1.5 of the appendix (ie standardised forms and personnel available to input and analyse data).
Merits and disadvantages	• As Incidence rates, except that they are more widely used by the industry and this make it easier to compare the performance of a given company to one of its competitors.

Use	• Health and Safety Executive, Government bodies.
	• Contractors, developers and infrastructure operators using frequency rates can be found in the literature. For example:
	  ◦ The Lost Time Injury Rate and Accident Frequency Rate (AFR) are used by Balfour Beatty[14] and Mace[15] amongst others.
	  ◦ HiPo is used by Balfour Beatty.

3.1.5 Summary

The literature suggests that the construction industry is increasingly resolute in tackling safety issues and, overall, in improving its safety performance. Nevertheless, the construction sector has proven to be relatively resilient in adopting alternative leading indicators that could have the potential to bring about improvement, whether these indicators are newly developed by researchers or imported from other industries.

Specifically related to this commission, it is important to emphasise that the safety performance of companies or construction sites belonging to the same company where different methods of construction are adopted should not be compared because of the different levels of risks associated with the different activities involved. Indeed, the risk profile associated with a project can have a major influence on the choice of safety metric. Studies have shown a dependency of the number of incidents occurring on site both with the method of construction and the level of pre-manufacturing involved[18]. Hence it is necessary to draw baselines for each one of the selected metrics for each type of project and risk profile. The same considerations apply whenever a company decides to assess the year-on-year change in safety performance.

The relative attractiveness of some of the metrics identified depends on their maturity, their timeliness, and their ability to drive the decision making and improvement process.

3.1.6 Conclusions and recommendations

There is considerable disparity between the metrics used in the UK and the USA. Clearly there are good reasons why UK metrics are to be preferred if the partners' strategic objectives are to be met. Whilst lagging indicators are the most commonly reported, they do not per se lead to improved safety performance in the short term. We therefore recommend the use of a combination of leading and lagging indicators.

Leading metrics

We recommend the use of two leading indicators: percentage of audited items in compliance and percentage of tasks which are pre-planned.

Percentage of items in compliance is widely used in the industry and can be used as part of a programme to reinforce positive behaviour which has been shown to have beneficial effects on safety performance[19]. It is simple, easy to understand, objective reliable (when used on sites and activities that are similar in nature), verifiable and can lead to the identification of useful improvement strategies. It is however relatively expensive, depending on the frequency of audits. Whilst no benchmarks exist, it is a useful metric for identifying trends over time.

Advanced planning and risk assessments are a statutory requirement, so data collection is easy and cost-effective. Additionally, the relationship between risk assessment and increased safety is well documented[20] , so the metric is closely related to strategic objectives. It is objective, reliable and verifiable.

Lagging metrics

Based on the literature review, we recommend the use of frequency rates, and in particular, number of days of lost work per 100,000 hours worked. The metric is widely used, objective, reliable, verifiable, cost effective and relates absolutely to strategic objectives. It also takes account of the severity of accidents. For maximum effect, root cause analysis should be undertaken for every lost time incident so that improvement strategies can be developed and implemented.

We further recommend that consideration should be given to supplementing this metric with the number of near misses recorded per 100,000 hours worked. This is a more difficult metric to deliver, not least because it requires increased cooperation of subcontractors and is prone to under-reporting. However, it is widely used and respected in the petrochemical industry.

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[11] Energy UK, 2017. Available at: https://www.energy-uk.org.uk/publication.html?task=file.download&id=6219 (Accessed: 10/05/2019).

[12] HSE, 2015. *Injury frequency rates*. Available at: http://www.hse.gov.uk/statistics/adhoc-analysis/injury-frequency-rates.pdf (Accessed: 08/05/2019).

[13] Balfour Beatty, 2015. https://www.balfourbeatty.com/media/29243/responsible.pdf (Accessed: 10/05/2019).

[14] Balfour Beatty, 2015. https://www.balfourbeatty.com/media/29243/responsible.pdf (Accessed: 10/05/2019).

[15] Mace, 2018. https://www.macegroup.com/about-us/financial-performance (Accessed: 10/05/2019).

[18] Rubio-Romero, J.C., Suárez-Cebador, M. and Abad, J., 2014. Modeling injury rates as a function of industrialized versus on-site construction techniques. *Accident Analysis & Prevention*, 66, pp.8-14.

[19] Duff, A.R., Robertson, I.T., Phillips, R.A. and Cooper, M.D., 1994. Improving safety by the modification of behaviour. *Construction Management and Economics, 12(1),* pp.67-78.

[20] Summerhayes, S.D., 2017. *CDM Regulations Manual 2015 (4th Edition)* Wiley Blackwell, Chichester, UK

3.2. LABOUR PRODUCTIVITY

3.2.1 Preamble

As stated in the Glossary of Terms, productivity is the ratio of output to input. Both outputs and inputs may be measured in different ways. For example, output may be measured in terms of m^2 of formwork, or value of work produced. Equally, input may be measured in terms of labour (cost or hours), plant (cost or hours), material (cost or quantity), investment (cost). Sometimes more than one input may be considered. This is called multi-factor productivity[22]. Labour productivity, with which this commission is principally concerned, is known as single factor productivity. Because the inputs and outputs may be measured in so many different ways, and can be combined to create an even greater plethora of labour productivity metrics, we start by listing the inputs and outputs.

Since output is produced by labour at the task level, and since much labour is subcontracted, productivity can only be measured and improved with the cooperation of subcontractors. This may be secured either by offering incentives of through the contract.

3.2.2 Outputs

Outputs are the principal determinant of the level of detail at which labour productivity is measured. They include:

- gross value added;
- value of work completed;
- earned value;
- earned hours;
- quantity of work performed (m^2 single leaf brickwork; no. of roofs completed; no. of units completed).

It isn't always necessary to measure outputs in every activity. The mean value theorem tells us that we need only concern ourselves with those quantities that are greater than the mean. Typically this means that we need measure only 20% of the outputs to capture 80% of the relevant information.

3.2.3 Inputs

Inputs may be any of the following.

- Total site operative time (the total hours for which operatives are paid). Labour productivity using this input is the figure normally required by estimators and may be used in high level productivity metrics[23].
- Available site operative time (= total site operative time minus unavoidable delays, principally breaks and weather). Labour productivity using this input is a measure of the quality of site management, the intrinsic capability of the labour force, and the buildability of the project[24].
- Productive site operative time (= available site operative time minus avoidable and unavoidable delays) is the time spent by operatives producing output, including any supporting activities such as transporting materials. Labour productivity using this input is a measure of the intrinsic capability of the labour force, and the buildability of the project[25].
- Total site management time[26].
- Total off-site design, management and support staff time during construction[27].

[22] De Valence, G. and Abbott, M., 2015. A review of the theory and measurement techniques of productivity in the construction industry. *Measuring Construction: Prices, Output and Productivity*.

[23] Horner, R.M.W. and Duff, A.R., 2001. *More for Less A Contractor's Guide to Improving Productivity in Construction*. CIRIA, London.

[24] Ibid.

[25] Ibid.

[26] Tsehayae, A.A., 2015. *Developing and optimizing context-specific and universal construction labour productivity models* (PhD Thesis, University of Alberta, Canada).

[27] Ibid.

- Total off-site design, management and support staff time pre-construction[28].
- Labour costs (including or excluding labour not employed on site)[29].

We identified the following labour productivity metrics.

- Gross value added/number of jobs
- Gross value added/total hours worked
- Gross value added/labour cost
- Value of work completed/total hours worked
- Value of work completed/labour cost
- Labour hours per plot
- Output of physical units/total hours paid
- Output of physical units/available hours worked
- Output of physical units/productive hours worked
- Delays
- Earned value/Actual cost
- Earned hours/Actual hours
- Construction Industry Institute (CII) Construction Performance Assessment (CPA)
- Productivity index

Details of the metrics whose use we recommend are provided below: details of the remaining metrics are provided in Appendix E.2.

[28] Tsehayae, A.A., 2015. *Developing and optimizing context-specific and universal construction labour productivity models* (PhD Thesis, University of Alberta, Canada).

[29] Ibid.

3.2.4 Output of physical units/total hours paid[30]

Output of physical units/total hours paid	
Method of measurement	Output, the amount of work produced, is measured conventionally either in terms of volume, area, linear metres, weight, or as an item where these measures are not appropriate. The more frequently output is measured, the more information becomes available and the quicker decisions can be made about what action needs to be taken. Output may therefore be measured daily, weekly, monthly, or simply at completion of a plot, site or project. Measurements may be taken either by site personnel or by intermittent visits by a quantity surveyor or similar. Unless output is measured only at the plot level (dealt with separately in Section 3.2.7) it is necessary to allocate the hours paid to the activities relating to each output. This is best done daily either by the operatives themselves, by first level supervisors, by continuous observation or at the end of each day by a visiting data gatherer since memories may be unreliable. In the late '60s, time and motion studies were used to derive this metric, largely for the purposes of setting bonus targets[31].
Merits	• It relates directly to strategic objectives. • It is a familiar measure that has been widely used both in practice and for the purposes of research. • The metrics are sufficiently detailed to allow performance to be compared at all levels including gang level, provided operatives' time is allocated to tasks. • It is a direct and objective measure, but depends on the commitment, dedication and integrity of those collecting the data.
Disadvantages	• It provides no diagnostic information about the causes of differences in productivity and therefore does not contribute significantly to effective decisions and process improvements. • It may be difficult to persuade operatives or supervisors to maintain adequate records. • Depending on the frequency of data collection by whom, it can be very expensive.
Use	• It is common practice to measure output at monthly intervals to inform payments. • Extensively used by researchers worldwide. • We have found no reports of use of this metric in practice other than when a payment by results scheme is in operation. Taylor Woodrow and Balfour Beatty are known to have used this method. It has almost certainly been used by other contractors.

[30] Horner, R.M.W. and Duff, A.R., 2001. *More for Less A Contractor's Guide to Improving Productivity in Construction*. CIRIA, London.

[31] Taylor, F.W. 1911. *Principles of Scientific Management.* Harper Bros, New York and London.

3.2.5 Output of physical units/available hours worked[32]

Output of physical units/available hours worked	
Method of measurement	Output is measured in the same way as in output of physical units/total hours paid. Available hours are the total paid hours minus unavoidable delays, principally paid meal breaks and weather. In addition to the measurements required for the previous metric, it is also necessary to measure the duration of the unavoidable delays. This can be achieved by any of the methods suggested in Section E.2.6.
Merits and disadvantages	The merits and disadvantages are shared with the previous metric, except that any changes recorded in this metric are caused either by delays or by differences in the intrinsic skill of the workforce. Since both are the responsibility of management, it can also be viewed as a measure of the quality of management.
Use	• It is common practice to measure output at monthly intervals to inform payments. • Extensively used by researchers worldwide. • We have found no reports of use of this metric in practice other than when a payment by results. scheme is in operation. Taylor Woodrow and Balfour Beatty are known to have used this method. It has almost certainly been used by other contractors.

3.2.6 Output of physical units/productive hours worked

Output of physical units/productive hours worked	
Method of measurement	Output is measured as before. Productive hours may be measure by activity sampling (see Section E.2.10), or, since productive hours worked are available hours worked minus avoidable delays, by measuring delays. These may be captured by the operatives themselves, at the end of each working day by a data gatherer (intermittent observation)[33], by foreman delay surveys[34] or by continuous observation. An alternative, as yet untried, would be to provide each operative with a mobile phone and Bluetooth headset so that the operatives themselves could record the start and end of each delay, together with its cause. This also has the potential to improve communications between operatives and supervisors.
Merits and disadvantages	• These are shared with the previous metric except that if the operatives themselves cannot be persuaded to record the data accurately, then the need for continuous observation and the associated costs may increase. The approach has the advantage that capturing the causes, frequency and duration of the delays provides valuable insights to management about the actions necessary to reduce delays and maximise labour productivity. Variations in output of physical units/productive hours worked indicate differences in the intrinsic skills of operatives.
Use	• As in Section 3.2.5.

[32] Horner, R.M.W. and Duff, A.R., 2001. *More for Less A Contractor's Guide to Improving Productivity in Construction*. CIRIA, London.

[33] Horner, R. M. W. and Talhouni, B. 1995. *Effects of Accelerated Working, Delays and Disruption on Labour Productivity.* Chartered Institute of Building, Englemere, UK.

[34] Tucker, R.L., Rogge, D.F., Hayes, W.R. and Hendrickson, F.P., 1982. Implementation of foreman-delay surveys. *Journal of the construction division*, *108*(4), pp.577-591.

3.2.7 Labour hours per plot

Labour hours per plot	
Method of measurement	This metric requires a record of the time spent by each operative on each plot. Labour hours may be divided into value adding hours, support hours or waste hours[35]. Because data is collected for each operative, metrics describing a given trade and/or a given level of qualification can readily be derived. It may be collected daily through timesheets, through continuous direct observation by a trained observer, using activity sampling, or through remote observations such as RFID or BLE (Bluetooth Low Energy), GPS, video recording, or time lapse photography[36]. Recent research has explored the potential to use wrist-worn devices such as Garmins to measure both heart rate and location simultaneously in an effort to distinguish between idle and productive time.[37]
Merits	• Relates to some strategic objectives. • Simple, meaningful and understandable. • Data is objective. • Can be used to derive metrics at the operative and qualification level.
Disadvantages	• Does not drive effective decisions and process improvements. • Relies on collaboration from subcontractors. • Unless continuous observation is used, the data may not be reliable, consistent or verifiable. • The range of vision of video recordings, time lapse photography, GPS and drones may be limited by the presence of solid objects. • The range of RFID and BLE is relatively short. Both need access to a power supply and a there may be interference form a variety of causes. • Expensive if continuous or remote observation used.
Use	• Time sheets are common when payment by results schemes are operated, and are generally regarded as useful and reasonably accurate. • Direct observation has been used extensively by researchers, but is rarely used in practice. • RFID has been extensively used for tracking materials and vehicles, and for checking the location of people largely for the purposes of safety. It has been used on construction sites in association with a gateway system[38] but we have found no description of its use for providing more precise locational information. • Drones and GPS are increasingly used to monitor muck-shifting operations and increase productivity. Balfour Beatty and BAM are two reported users.[39] • Both video recording and time lapse photography have been used on occasion, but both are intrusive and have limited field of vision.

3.2.8 Summary

The relative attractiveness of some of the metrics identified depends on the purpose for which they are to be used and the method of measurement. In Appendix E.2 we have included only those methods of measurement where significant use has been reported. Of these, the most widely reported appears to be the CII method, but its use is confined to the USA and Canada. It is based on earned value and requires the existence of baseline measures of labour productivity to convert quantities in one activity to equivalent quantities in another. Popular in the 1980s and

[35] Tsehayae, A.A., 2015. *Developing and optimizing context-specific and universal construction labour productivity models,* (PhD Thesis, University of Alberta, Canada).

[36] Zhao, J., Seppänen, O., Peltokorpi, A., Badihi, B. and Olivieri, H., 2019. Real-time resource tracking for analyzing value-adding time in construction. *Automation in Construction,* 104, pp.52-65.

[37] Son, W., 2017. *Exploring the feasibility of measuring individual labor productivity using a wearable activity tracker* (Doctoral dissertation, The University of Texas at Austin).

[38] Costin, A., Pradhananga, N. and Teizer, J., 2012. Leveraging passive RFID technology for construction resource field mobility and status monitoring in a high-rise renovation project. *Automation in Construction, 24*, pp.1-15.

[39] http://www.constructionmanagermagazine.com//onsite/earthworks-machines-take-intelligence-test/ (Accessed: 19/06/2019).

1990s in the USA, activity sampling has not been widely used in the UK, though there are isolated reports of the use of BRE's Calibre.

Inevitably, the cost of data collection must be weighed against the benefits it brings. If a comprehensive understanding of the construction process is required, it is necessary to allocate labour hours to each activity. This may be achieved either by the operatives themselves, most commonly when a payment by results scheme is in operation, or by continuous observation by a trained observer (which significantly increases the cost). More recently, there are a number of reports of the use of automated data collection, although these are almost entirely in a research setting.

3.2.9 Conclusions and recommendations

If the purpose is to understand the process of construction in detail, to determine how much and what type of labour resource is consumed by each activity, to take account of the context in which the work is undertaken, the local conditions and constraints, there is no substitute for continuous observation. If on the other hand the requirement is simply to determine the labour hours expended by each trade on each plot, then as an alternative to direct observation RFID or BLE may offer advantages, particularly if supplemented by intermittent observation and "diary keeping". However, if automated tracking is to be used, it will be necessary to position beacons with great care to ensure that the presence of all those working on the relevant plot is accurately recorded, and that the system does not record people who are working nearby but not on the relevant plot. In terms of outputs, in a repetitive process like housebuilding, the plot is useful unit of measure, since it can readily be converted into other outputs such as quantities of materials or value.

Finally, we make the observation that recording inputs and outputs in a factory environment is significantly easier than on site. Equally, if OSM is widely adopted, the collection of on-site productivity data becomes easier because there are fewer activities to monitor. We have not found reference to these advantages of offsite manufacture in the literature, but they certainly provide enhanced opportunities to improve on-site and off-site productivity.

Based on the foregoing discussions, our recommendations are as follows.

1. If detailed information about the process of construction, its context and constraints is required, and if the labour force cannot be used to keep the necessary records, then direct, continuous observation by a trained observer should be used.
2. If the purpose is simply to determine the reduction in labour inputs occasioned by off site manufacture, then the use of RFID or BLE should be piloted after suitable investigation of any constraints or shortcomings that might arise. In any case, it would be advantageous, not only to the AIMCH project but to the whole industry if RFID were supplemented by direct observations and activity sampling so the relative merits of each approach could be determined in more depth.

3.3. QUALITY

3.3.1 Preamble

In this project quality has been defined as '*the extent to which work meets or exceeds the specification*'[40]. Accordingly, a quality issue can be described as '*an issue that effects the project so that work needs to be redone, modified or compromised to a lower standard than originally agreed*'[41]. Embedded in the definition of quality is the common understanding that any process adopted for carrying out work has flaws and that, as a result, errors and defects can be found in the final output. So quality is an indirect measure of both how good the process is and how well it was implemented.

Quality, or more correctly the lack of it, has a direct impact on a series of other performance indicators such as cost, time, material waste and predictability.

- **Cost:** if rework must be undertaken due to the lack of quality, direct and indirect costs associated with it will lead to an overall increase in the project cost. CITB[42] estimated that around 21% of the total cost of a construction project is due to error (though this includes the cost of process errors as well as errors in the finished product). Details of the impact that errors have on direct and indirect costs are shown in Figure 1.
- **Time:** depending on the project stage at which the lack of quality is identified, a delay in the project completion might result if rework is required, and customer satisfaction can be impaired if defects are not remedies promptly.
- **Material waste:** Rework often leads to waste of materials.
- **Predictability:** lack of quality leads to increases in costs, waste and, sometimes, in programme duration. If not correctly estimated and accounted for, these variations may affect all a project's performance indicators.

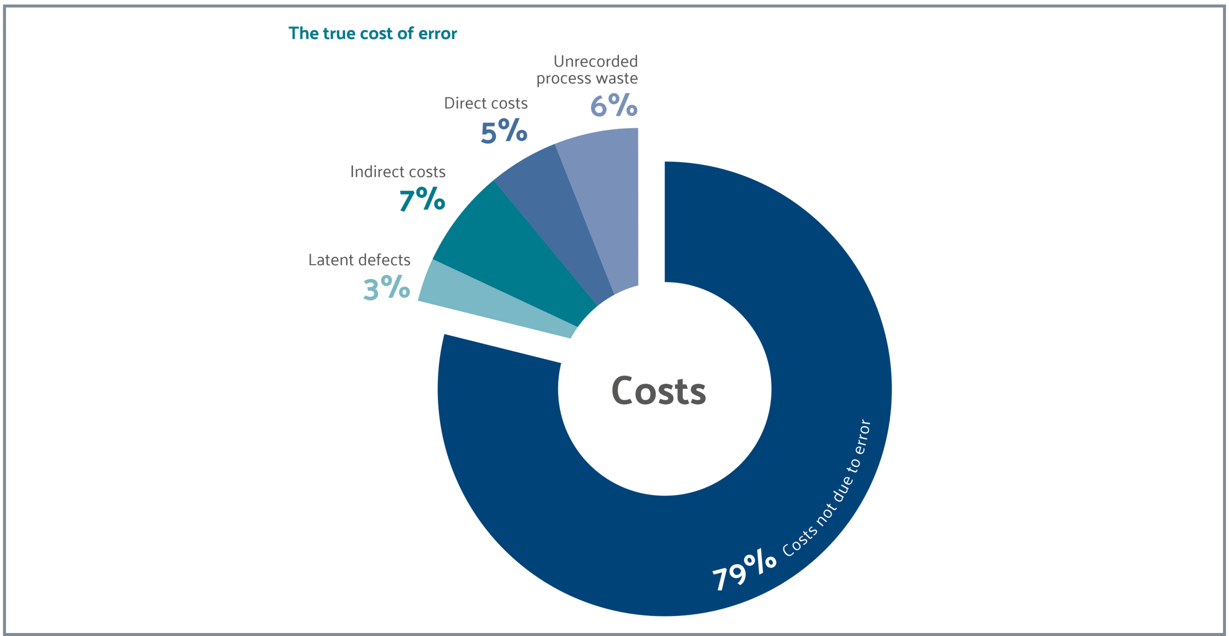

Figure 1. Impact of errors on the cost of a construction project (from CITB 2015[42]).

[40] WLC, 2019. *AIMCH – Work package 2: Productivity mapping and literature review. Glossary of terms.*

[41] The KPI working Group, 2000. *KPI Report for The Ministry for Construction*. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/.../file16441.pdf (Accessed: 28/05/2019).

[42] CITB, 2015. *Get it right. A strategy for change.* Available at: https://getitright.uk.com/reports/ (Accessed: 27/05/2019).

One of the complexities in measuring quality is that quality issues might arise due to a mix of tangible and intangible causes the most common of which are[41,43 in 44,45]:

- Poor workmanship
- Incomplete or wrong design and specifications
- Poor material/components handling
- Defective materials
- Inadequate planning
- Poor communication
- Inadequate supervision

Quality performance metrics can be based on either qualitative or quantitative data. The former include results of post-occupancy customer surveys, project management information, and type of quality issues: the latter include cost data, quantities data, and frequency data. Each quality metric identified from the literature review is discussed separately in the section below starting with those derived from qualitative data.

We identified the following quality-related metrics.

- HBF star rating
- Field Rework Index (FRI)
- ISO 9001 Accreditation
- Yield
- Quality rating
- Costs due to error/total construction cost
- Number of reportable items
- Number and type of items that did not pass visual inspection

Details of the metrics whose use we recommend are provided below: details of the remaining metrics are provided in Appendix E.3.

[43] National Economic Development Office (NEDO), 1983. *Faster Building for Industry.* NEDC, London.

[44] Korff, M., 2017. Case studies and monitoring of deep excavations. In *Geotechnical Aspects of Underground Construction in Soft Ground* (pp. 23-31). CRC Press.

[45] Barton, T., 2018. Attitude, Culture, Leadership & Planning. Quality in construction summit, 27 November 2018, Manchester, UK. Available at: https://summits.ukconstructionweek.com/qic/quality-in-construction-summit-2018#presentations (Accessed: 28/05/2019).

3.3.2 HBF star rating

HBF star rating	
Method of measurement	This post-occupational metric is an indirect measure of the quality of a new house. The HBF star rating scheme rates house builders which are members of the Home Builders Federation based on the customers' perception of the purchase they have made. This metric is determined via the results of two surveys[46]: one showing clients' satisfaction 8 weeks after the completion of the purchase, one showing the same after 9 months from the purchase. Although issued surveys contain 20 questions[47], only the '*Would you recommend your builder to a friend?*' one contributes to the star rating[47,48]. The percentage of customers answering "Yes" to this question determines the number of stars assigned to a company according to the bands system outlined below.
Merits	• Simple, easy to understand, and mature. • No direct costs associated to data collection and processing.
Disadvantages	• Highly subjective. It might be affected by the performance of the customer service department of a company and not only by the quality of the building purchased. • Only customers of HBF members are asked to participate in the survey. • Participation is not compulsory for house buyers. This raises issues around the completeness and hence the representativity of the collected data (eg the response rate for the 2017/2018 survey was just over 61%[47]). • It does not provided information on how that level of quality has been reached. For example, it does not provide details about the type of rework carried out prior to or after the hand-over of the keys.
Use	• All HBF members. Examples include Barratt Development, Stewart Milne Homes, Persimmon, Taylor Wimpey, Bellway, etc.[48,49]

% of customers that answered "Yes"	Number of stars
90%+	5 stars
80% - 89.9%	4 stars
70% - 79.9%	3 stars
60% - 69.9%	2 stars
50% - 59.9%	1 star

[46] https://www.nhbc.co.uk/homeowners/completenewhomessurvey/ (Accessed: 27/05/2019).

[47] *2017/2018 National new home customer satisfaction survey*. Available at: https://www.hbf.co.uk/documents/8389/CSS_HBF_Brochure_2019_with_table.pdf (Accessed: 27/05/2019).

[48] http://www.brand-newhomes.co.uk/hbf-house-builder-star-rating-scheme.htm (Accessed: 27/05/2019).

[49] http://www.stewartmilne.com/award-winning-people.aspx (accessed: 29/05/2019).

3.3.3 Quality rating

Quality rating	
Method of measurement	Defined by the formula below. $$Quality\ rating\ (\%) = \frac{Total\ construction\ capital\ cost - Cost\ of\ post\ occupation\ defects}{Total\ construction\ capital\ cost} \times 100$$
Merits	• Simple to determine, verifiable, objective, simple to understand. Data should be available within each organisation. • It describes the "presence" of quality rather than the lack of it. • Can be used at any level of granularity – house, site, region, company. • Benchmarks exist and can be used to compare the performance of a company with the rest of the industry. • Relates to strategic objectives.
Disadvantages	• Does not provide information on the type of issues encountered and, most importantly on their frequency of re-occurrence. • Has no impact on the construction phase (ie on the phase during which errors could be avoided or rectified at a minor cost). No improvement can be achieved in the project monitored. • Does not account for re-work done before handing over the property to the customer. This is consistent with the definition given by CLC of quality: '*The freedom from faults of new homes when they are handed over to the customers*'[50].
Use	• NHBC, which developed benchmarking values for the housing sector. • It is the metric suggested by CLC for assessing the performance of a company in terms of product quality[51].

3.3.4 Number of reportable items

Number of reportable items	
Method of measurement	This may be the number of reportable items identified during internal audits or audits carried out by NHBC. A reportable item as defined by NHBC is any item that, if left outstanding, could '*prevent Warranty or Building Control finalling [sic]*'[52]. Reportable items have been introduced by NHBC and form the bulk of their Consultative Inspection Report and of their online NHBC Portal[53].
Merits	• Easy to determine, reliable, objective and verifiable. • If consistently and constantly adopted, it can induce a behavioural change in the workforce because it provides timely information on the type of issues and the corrective actions to adopt. • Allows the performance of a project to be tracked while still ongoing (ie during the construction phase).
Disadvantages	• Costs associated with data collection (eg site observer, auditor). • Subject to site observer/auditor bias and experience. • Not coupled to cost information.
Use	• Any property developer and or/company applying for NHBC accreditation.

[50] CLC, 2018. *Smart construction dashboard. Housing.* Available at: http://www.constructionleadershipcouncil.co.uk/building-metrics/ (Accessed: 27/05/2019).

[51] CLC, 2018. *Innovation in building workstream. Housing industry metrics.* Available at: http://www.constructionleadershipcouncil.co.uk/building-metrics/ (Accessed: 27/05/2019).

3.3.5 Summary

Quality is an important metric since it has a high impact on customer satisfaction, reputation and eventually, profitability.

With the exception of a user satisfaction survey, all quality metrics require an audit of the work executed and the identification of deficiencies. They are therefore relatively expensive. In general, metrics take two forms: the number of defects and the cost of rectification. Whilst the number of defects can be relatively easily captured, metrics based on costs require comprehensive and accurate record keeping. In both approaches, it is necessary to analyse data thoroughly if the causes of deficiencies are to be fully understand and addressed.

3.3.6 Conclusions and recommendations

In applying quality metrics, it is important to distinguish between deficiencies in the process and deficiencies in the product. Internal audits are most effective for early rectification of deficiencies, whilst external audits generally provide information only after completion of the work.

For Barratt, and L&Q, the HBF star rating and the Number of reportable items are widely recognised, objective, mature, relate closely to strategic objectives and are easily administered so we recommend that their use should be continued. For similar reasons, and because and its use is suggested by CLC, we recommend that the NHBC Quality rating should also be used by Barratt, L&Q, and Tarmac. This has the advantage of identifying the causes of deficiencies allowing improvement measures to be determined and implemented, but as previously noted, requires the maintenance of comprehensive and accurate cost records. In addition, we recommend that Forster Roofing should continue to use the number of reportable items as a measure of quality.

[52] NHBC. *NHBC Extranet user guide. Site management made easy*. Available at: http://www.nhbc.co.uk/NHBCPublications/LiteratureLibrary/extranet/filedownload,32548,en.pdf (Accessed: 27/05/2019).

[53] http://www.nhbc.co.uk/Builders/Register/support/construction/ (Accessed: 27/05/2019).

3.4. COST

3.4.1 Preamble

From the outset, it is important to define what is meant by cost. We need to be clear whether we mean initial (capital) costs (including site preparation costs, professional fees and construction costs) or life cycle costs (site acquisition + capital costs + renewal + operation + maintenance + end of life costs)[54]. Whilst the growing importance of life cycle costs is recognised, so is the difficulty in measuring them. For the purposes of this report, we therefore take cost to mean the construction cost of a house, since one of the aims of the AIMCH project is to compare the construction costs of houses built conventionally (brick and block construction) with houses built offsite to varying degrees. Even then, some further clarification is necessary. The cost of a house to the client is the price for which the developer or builder is prepared to sell it. The cost to the builder is the cost of acquiring the land, of design, marketing and finance, of the direct resources required to effect the construction including preliminaries, and the cost of any customer aftercare service including rectification of defects. Again, for the purposes of this report, we will define construction cost simply as the cost of the direct resources required to effect the construction (labour, plant materials, subcontractors) including preliminaries and rectification of defects but excluding all other costs, which are likely to be the same independent of the degree of offsite manufacture.

Two types of cost-related metrics can be defined: absolute performance metrics and relative performance metrics[55.] Absolute performance metrics consist of metrics in which costs have been normalized with respect to either a project-related physical or functional measure (eg the internal gross floor area or the number of bedrooms) or a financial one (eg the capital cost). Relative performance metrics, on the other hand, consist of metrics that allow a comparison between planned cost values and actual cost values. Examples of metrics belonging to this category are *Cost variance* and *Cost growth*. These metrics may also be used to measure predictability (see Section 3.6)

When comparing costs, it is important to take account of any temporal and/or locational differences that might impact the construction cost.

The cost-related metrics we identified are as follow.

- Average construction cost/m^2 (GIFA)
- Construction cost/bedroom
- Average construction cost/plot
- Construction cost/item or element
- Cost variance
- Change in cost of construction
- Cost of rectifying defects
- Prelims cost/capital cost
- Cost growth (%)
- Phase cost ratio
- citiBLOC/m^2

Details of the metrics whose use we recommend are provided below: details of the remaining metrics are provided in Appendix E.4.

[54] *International Cost Management Standards: Global; Consistency in Presenting Construction Costs (2nd Edition).* forthcoming

[55] Choi, J., Yun, S. and de Oliveira, D.P., 2016. Developing a cost normalization framework for phase-based performance assessment of construction projects. *Canadian Journal of Civil Engineering*, *43*(12), pp.1075-1086.

3.4.2 Average construction cost/plot

Average construction cost/plot	
Method of measurement	This metric is the total construction cost divided by the number of plots.
Merits	• Relates to strategic objectives, relatively easy to determine, simple, objective, widely understood, reliable and verifiable. • One of the principal determinants of profitability.
Disadvantages	• Takes no account of differences in quality or layout. • Requires accurate monitoring of costs of all resources used in construction. • Preliminaries may not be accounted for consistently.
Use	• Used by Barratts, Taylor Wimpey[56] and others[57].

3.4.3 Cost of rectifying defects

Cost of rectifying defects	
Method of measurement	This is the cost associated with 'rectifying all defects in the maintenance period between [the moment the asset is ready to be handed over to the client and End of the Contractually Agreed Period for Rectifying Defects […], expressed as a percentage of construction cost [at the moment the asset is ready to be handed over to the client].[58] This metric is very similar to that introduced as quality indicator in Section E.3.4. They differ from each other because of the timeframe over which they are measured: the quality indicator is measured starting from the beginning of the construction; the cost indicator is measured starting from the end of construction.
Merits	• Relates to strategic objectives. • Relatively simple to determine, objective, reliable and verifiable. • Provides a good indication of quality of workmanship and quality control. • Closely linked to customer satisfaction.
Disadvantages	• Requires maintenance of accurate costs of rectification. • Provides no information on the type of work carried out and, most important, whether defects were due to design, material or workmanships issues. • As a result, does not comprehensively inform improvement programmes.
Use	• One of the cost-related metrics suggested by the KPI Working Group (2000).[58]

[56] https://www.investorschronicle.co.uk/2016/09/23/shares/understanding-housebuilders-eRoxGU1pIpMHLF8TEXp8eO/article.html (Accessed: 17/06/2019).

[57] Urban&Civic plc, 2016. *Presentation of full year results to 30 September 2016*. Available at: https://www.urbanandcivic.com/files/2614/8102/5343/UrbanCivic_Presentation_of_Full_Year_Results_2016.PDF (Accessed: 17/06/2019).

[58] KPI Working Group, 2000. *KPI Report for the Minister for Construction*.

3.4.4 Construction cost/item or element

Construction cost/item or element	
Method of measurement	This is the cost of an item in a bill of quantities or schedule of elements. It is often expressed per unit quantity.[59,60]
Merits	• Identifies cost drivers and therefore directs attention to where improvements may be made. • Allows comparisons at a detailed level of different design solutions (eg large block panels vs conventional blockwork). • Helps to determine and control differences between actual and predicted costs.
Disadvantages	• Requires accurate allocation of costs of all resources used in construction. • Preliminaries may not be accounted for consistently.
Use	• Widely adopted in different sectors of the construction industry.[59,61]

3.4.5 Summary

Metrics based on costs are amongst the most widely used and the most controversial. Until the advent of ICMS[62], no internationally accepted standard method of measurement existed. Additionally, there is confusion between metrics for financial accounting and cost management. The former is bound by statutory requirements, whilst the implementation of the latter varies widely from company to company. Even then, inaccuracies in the collection and allocation of costs abound. (eg Carillion, Kier). Because of the difficulties in assigning costs at high levels of granularity, the most widely used metrics are high level.

3.4.6 Conclusions and recommendations

In developing metrics for AIMCH, it is even more important to be quite clear about the purposes of the metrics. Since the principal strategic objective is to determine the difference between the construction costs of houses built conventionally in brick and block and those constructed using varying degrees of off-site manufacture rather than effecting reductions in costs in existing processes, it makes sense to measure costs at the plot level. At the same time, since certain types of off-site manufacture are expected to reduce deficiencies in the finished product, it makes sense to separate out construction costs and the cost of rectification of defects.

At the same time, if the intention is to compare the costs of different construction methods with one another, eg large block panels with conventional brick and block or pre-cut roof tiles with cut-on-site, it will be necessary to allocate costs at the elemental level. In some cases, this may involve re-designing the existing cost monitoring systems to break costs down into labour, plant and materials.

To satisfy the principal strategic objective for Barratt and L&Q, we recommend that the principal metrics should be the average construction cost per plot and the average cost of rectification of defects per plot. Costs should exclude the costs of foundations, which are assumed to be the same for conventional and OSM, but should include the costs of prelims which may vary between conventional and off-site construction. The costs of solutions using off-site manufacture should include the costs of investment in the necessary facilities, design of bespoke solutions, manufacturing, logistics and assembly. Clearly, costs will have to be compared on plots of similar characteristics in terms of quality and functional specification eg two bedroom terraced social housing.

To compare the costs of individual elements (eg walls roofs, etc.), it will be necessary to collect construction costs related solely to those elements. Of these, the most difficult will be labour hours and preliminaries (eg additional cranage or reduction in use of forklift to deliver materials). To accomplish this, it may well be necessary to carry out direct observations.

59 AECOM, 2017. *SPON'S Architects' and builders' price book 2017.*

60 RICS, 2012. *NMR1 New rules of measurement. Order of cost estimating and cost planning for capital building works.*

61 BCIS, 2018. *Comprehensive building price book – minor works. 35th edition 2018.*

62 *International Construction Measurement Standards,* 2017. International Construction Measurement Coalition.

3.5. TIME

3.5.1 Preamble

In the context of this report, we mainly refer to time as to the elapsed time between two events; in other words, we refer to time as duration. At a very high level, this elapsed time corresponds to the '*programme duration*' of a project or to the time interval between two project milestones which have been defined by one or more stakeholders as boundaries of a project phase.

The hierarchical structure proposed in Figure 2 shows how these coarse metrics (ie programme and phase durations) can be broken down into their constituents. At the lowest level, they consist of:

- **value adding time**, which is defined as all the time spent on-site creating value. This includes time spent correctly building elements and assembling components, but it does not include time spent in reworking activities.
- **support time**, which is defined as the time spent on-site during which no adding value activity takes place but, at the same time, it cannot be avoided (eg time spent coordinating a project, hauling materials).
- **waste time**, which is all the time spent on-site without creating value and that could be avoided if the construction process was efficient. Examples of waste time are time spent waiting for materials and time spent in re-working activities.
- **Time not on-site:** this is the time during which no construction activity takes place on-site (ie outside working hours).

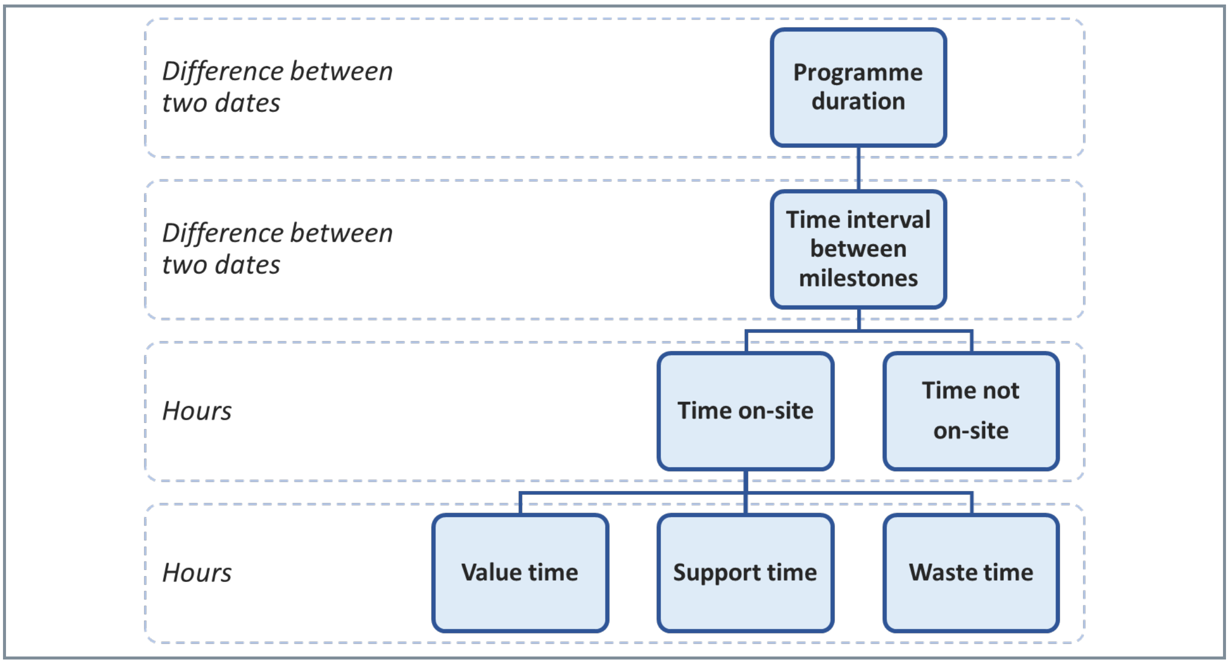

Figure 2 Hierarchy describing the relationship between a programme duration and its constituents. On the left-hand side of the picture the most commonly used units of measure are listed. The distinction of time at the lowest level is based on the concept of waste in lean management[63].

When comparing two or more projects by using metrics based on time spent on-site, it is important to bear in mind that these are not elapsed times anymore: they are the sum of the time spent on-site by each single resource (ie workers) involved in the construction project. Hence the strong relationship between time-related metrics and those productivity-related metrics in which input is given by time (eg *Labour hours per plot*, *Output of physical units/total hours paid*).

The time-related metrics we identified are as follow.

[63] https://leanconstructionblog.com/The-Concept-of-Waste-as-Understood-in-Lean-Construction.html (Accessed: 19/06/2019).

- Overall time (or Programme duration)
- Time/output of physical units
- Time per plot
- Time/m^2
- Delivery speed
- Change in time for construction
- Projects schedule variation (%)
- Schedule growth (%)
- Project schedule factor

Details of the metrics whose use we recommend are provided below: details of the remaining metrics are provided in Appendix E.5.

3.5.2 Time/output of physical units

Time/output of physical units	
Method of measurement	• This metric is defined as the average time required to produce a unit of given output. Sanchez et al. (2016)[64] call it '*Time per unit*'. When the time considered coincides with the total hours paid or with the available hours worked, this metric can be obtained as the inverse of the productivity metrics described in Section 3.2.4 and Section 3.2.5. Data can be obtained from project timesheets or records, Gantt charts or visual inspections.
Merits	• Relates to strategic objectives, objective, verifiable. • Relatively easy to determine. Sufficiently detailed to allow performance to be compared at different levels (eg gang, operative).
Disadvantage	• Requires monitoring the start and end times of each output, so cost-effectiveness depends on the level of detail required. • Costly and time-consuming in-depth analysis of collected data is required if details on the type of activities carried out are of interest. • It can be misleading if '*Time on site'* is used for deriving it.
Use	• Widely used in different sectors of the construction industry (eg housing[65], oil and gas[66]). • Benchmarking values for construction activities can be found in the literature (eg BCIS price books[67]).

[64] Sanchez, A. and Joske, W., 2016. Metrics dictionary. In Delivering Value with BIM: A Whole-of-Life Approach (pp. 297-336).

[65] CLC, 2018b. *AIMC4 Casestudy*. Available at: http://www.constructionleadershipcouncil.co.uk/wp-content/uploads/2018/10/181022-CLC-Casestudy-AIMC4.pdf. (Accessed: 25/02/2019).

[66] Rui, Z., Li, C., Peng, F., Ling, K., Chen, G., Zhou, X. and Chang, H., 2017. Development of industry performance metrics for offshore oil and gas project. *Journal of Natural Gas Science and Engineering*, *39*, pp.44-53.

[67] BCIS, 2018. *Comprehensive building price book – minor works. 35th edition 2018*. RICS.

3.5.3 Time per plot

Time per plot	
Method of measurement	This metric is defined as the time required to complete works on a given plot and at the highest level, requires a record only of the start and completion dates. It is a particular case of the metrics introduced in Section 3.5.2 where the output unit is the 'plot'. Depending on the level of accuracy required, it can be determined by considering time-on site or the elapsed time between the start of works on that plot and its completion. If measures are taken at the level of labour hours, this metric coincides with the productivity metric Labour hours per plot (see Section 3.2.7).
Merits	• As Section 3.5.2. • Useful when a project can be sub-divided in plots of equal characteristics (ie, same size, same boundary conditions, same construction type).
Disadvantage	• As Section 3.5.2. • Inaccuracies can be introduced when comparison involves plots with different characteristics. • Limited capability of producing benchmarking values because it requires plots with same characteristics in order to be applied.
Use	• No examples of use in practice were found in the literature, though the average time of construction per plot can readily be calculated by most contractors.

3.5.4 Summary

Time can be measured in a variety of ways each with a variety of meanings. We need to be very clear what time is of interest. In many publications, time is loosely or imprecisely defined. Moreover, construction context which can have a big impact on time is often ill-defined. Many of the metrics in regular use are concerned with variances between planned and actual programme. Relatively few are normalised to allow useful comparisons to be made.

3.5.5 Conclusions and recommendations

In satisfying the principal strategic objectives of Barratt and L&Q, the average elapsed construction time per plot is the metric of interest, since this defines when a house will be ready for the customer. Moreover, this metric can be easily converted in the elapsed time per m^2 whose use has been suggested by CLC (see Section E.5.2 for more details on the use of this metric). As with costs, times will have to be compared on plots of similar characteristics in terms of quality and functional specification. Additionally, because urgency is driven by demand, it will be necessary to ensure that that build contexts are comparable too if comparisons between on-site and off-site construction are to be meaningful. To achieve this, it may be necessary to compare both average and minimum construction times. Again, we recommend that the time to construct foundations is excluded since these will be more or less the same for on- ad off-site construction. For off-site construction, consideration will have to be given to any time required for bespoke design, for manufacture, and for transportation as well as assembly on site. We recommend that the time taken for each of these phases is recorded.

For Tarmac, Stewart Milne and Forster Roofing, the time required to construct the relevant elements is the focus of attention. It will therefore be necessary to record the start and completion times of each relevant activity. This may be achieved by the operatives themselves, by supervisors or by intermittent or continuous observations by an independent observer.

3.6. PREDICTABILITY

3.6.1 Preamble

Predictability is equally important to the developer and the customer. Both require certainty about cost, time, and quality. Predictability of safety, productivity, labour requirements, quality and material waste all contribute to predictability of cost and time. Thus, project predictability can be measured by the extent to which the project's objectives in terms of time and cost are met.

Cost and time predictability are two of the KPIs that were introduced in the construction industry after the Egan 1998 report[68]. Since 1999, they have included in the Government's National Construction Industry Key Performance Indicators (KPIs)[69] where they are defined as the number of projects completed on time and within budget[70]. National results are published annually in the Industry Performance Report produced jointly by Glenigan and Constructing Excellence[71]. Time predictability is expressed as a measure of how closely the project was delivered to the original schedule, and cost predictability expressed as a measure of how well outturn costs compared with original budget. Cost and time predictability can be measured at any stage in project realisation from design through whole life, and at any level, from component or element to whole project level.

The Farmer review identified low predictability as one of the critical symptoms of failure and poor performance[72].

In Lean Thinking, predictability is embodied in the notion of variability[73] and a primary objective of improvement interventions.

The scope of this research is the construction stage. If cost and time predictability are measured in accordance with the definitions and calculation methods detailed in the KPI Report to the Minister for Construction[74] they are defined as the 'change between the actual construction cost or time at the available for use point and the estimated construction cost or time at the commit to construct point, expressed as a percentage of the estimated construction cost or time at commit to construct. For the purposes of this report, our consideration of predictability is confined to the construction and defects remediation stages and specifically from completion of foundations to hand over to the customer plus the cost and time involved in remedying defects from completion to the end of the defects liability period. However, when comparing off-site and on-site manufacture, it will be wise to measure predictability in the design, manufacture, and transportation phases as well as the assembly phase.

The predictability metrics we identified are as follow.

- Time predictability – change in completion date
- Time predictability – average percentage overrun
- Cost predictability
- Cost and time predictability – SmartSite KPIs
- Safety, productivity, quality and material waste predictability

Details of the metrics whose use we recommend are provided below: details of the remaining metrics are provided in Appendix E.6.

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[68] Egan, J., 1998. *Rethinking construction*. Department of Environment, Transport and the Region.

[69] The KPI Working Group, 2000. *KPI report for the Minister for Construction*, Department of the Environment, Transport and the Regions (DETR).

[70] Ibid.

[71] http://constructingexcellence.org.uk/kpi-reports/ (Accessed: 17/06/2019).

[72] Mark Farmer, 2016. *The Farmer review of the UK construction Labour Model, Modernise or Die*, The Construction Leadership Council.

[73] Thomas, H.R et. Al. 2002. Reducing Variability to Improve Performance as a Lean Construction Principle *Journal of Construction Engineering and Management*, vol 128, Issue 2.

[74] The KPI Working Group, 2000. *KPI report for the Minister for Construction*, Department of the Environment, Transport and the Regions (DETR).

3.6.2 Time predictability – average percentage overrun

Time Predictability – average percentage overrun	
Method of measurement	The average overrun is the average number of weeks or days by which the actual construction duration exceeds the construction duration first anticipated expressed as a percentage of the anticipated duration.
Merits	• Simple, reflects strategic objectives, understandable, objective, cost effective and verifiable. • Can be rolled up from plot to site to organisation to national level. • Provides an indication of the severity of overruns. • Closely related to National KPIs.
Disadvantages	• Provides no information on the causes or severity of overruns so cannot contribute to improvement strategies.
Use	• Widely, but especially by the National Audit Office.[75]

3.6.3 Cost predictability – average percentage overrun

Cost predictability	
Method of measurement	Cost predictability can be measured in the same way as time predictability, but substituting actual and estimated costs for actual and planned durations.
Merits & disadvantages	• Generally as Section 3.6.2, but recognizing that the collection of cost data is more complex than the collection of time data because of the need to allocate direct costs and prelims to each plot or element.
Use	• Widely, but especially by the National Audit Office.[76]

3.6.4 Summary

Predictability is of prime importance to developers, builders and customers alike. All seek certainty. The only metrics that are reported to be widely used are the National Construction Industry Key Performance Indicators. These however do not directly reflect the AIMCH partners' strategic objectives. Predictability can be determined for any chosen metric from the difference between actual and planned performance. However, cost and time predictability are umbrella metrics that capture the impact of lack of predictability (variability) in other, contributory metrics.

3.6.5 Conclusions and recommendations

In the light of the AIMCH partners' strategic objectives, and in the pursuit of simplicity and consistency we recommend that time and cost predictability should both be measured in terms of the average percentage overrun. For complete houses, it should be measured at the plot level (ie average percentage overrun per plot). It can however be measured in the same way for any element or activity in the construction process eg walls, floors or roofs.

[75] HM Treasury and Cabinet Office, 2012. *Assurance for Major Projects*. Report by the Comptroller and Auditor General.
[76] Ibid.

3.7. EFFICIENCY

3.7.1 Preamble

The literature review indicates that the term efficiency in construction is used without a clear or consistent definition[77]. As a result, efficiency measurements are implemented and results interpreted in various ways. Examples of definitions include the following.

- Efficiency is the ratio of input to output; the relationship between efforts to outputs[78].
- Efficiency is fundamentally reducing the amount of wasted resources that are used to produce a given number of goods or services (output)[79].
- In the field of quality management (QM), efficiency refers to doing things right, ie whatever is performed, it is performed in the most suitable way, given the available resources[80].

For this study the WP2 team has agreed that efficiency is defined as doing more with less. A process is efficient if waste is minimised ie if maximum output is produced by a minimum of resource.

In the Glossary of Terms (Appendix C), waste is defined as 'anything that does not add value for the client'. In the construction process, waste is associated not only with waste of materials, but with other activities that do not add value such as waiting time, delays, and unnecessary transport, etc[81]. Construction waste therefore can be divided into two types a) material waste and b) process waste

Material waste is defined as all the material that is delivered to a site but which is not used for the purpose for which it was purchased[82]resulting in additional costs. Metrics for material waste are discussed in detail in Section 3.8.

Based on our agreed definition of efficiency, efficiency can be measured in terms of minimising or eliminating waste in on-site construction processes. Several studies have recommended applying lean principles to improve the efficiency of onsite construction operations including housing[83,84].

In lean thinking, constructions process activities can be divided into value adding and non-value adding activities. Non-value-adding activities can be divided into two categories: supporting activities and waste. Supporting activities are work activities that do not directly add value to the output but cannot be removed, as they are essential in carrying out a task. These include for example: necessary transport activities, cost estimating activities, reading drawings, cleaning up the workplace etc. On the other hand, the wasteful activities are those that are not necessary. They result in additional cost, time or both, and can be eliminated from the construction process without diminishing the value of the work.

Seven types of waste are defined in lean construction: waiting, unnecessary motion, defects, unnecessary transportation, unnecessary inventory, overproduction, and over- processing[84]:

- ***Waiting:*** Waiting refers to the periods of inactivity during which no value-added activity is performed. The waste of waiting may include people waiting for the completion of a preceding activities, waiting for information, material or plant, and indeed, any unnecessary idle time. Delay is one of the productivity metrics considered in Section 3.2.

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[77] Sundqvist, E., Backlund, F. and Chronéer, D., 2014. What is project efficiency and effectiveness?. *Procedia-Social and Behavioral Sciences, 119*, pp.278-287.

[78] Park, J.L., Yoo, S.K., Lee, J.S., Kim, J.H. and Kim, J.J., 2015. Comparing the efficiency and productivity of construction firms in China, Japan, and Korea using DEA and DEA-based Malmquist. *Journal of Asian architecture and building engineering*, 14(1), pp.57-64.

[79] https://www.investopedia.com/terms/e/efficiency.asp (Accessed: 17/06/2019).

[80] Sundqvist, E., Backlund, F. and Chronéer, D., 2014. What is project efficiency and effectiveness?. *Procedia-Social and Behavioral Sciences,* 119, pp.278-287.

[81] Rahman, H.A., Wang, C. and Lim, I.Y.W., 2012. Waste processing framework for non-value-adding activities using lean construction. *Journal of Frontiers in Construction engineering, 1(1),* pp.8-13.

[82] Defra, 2012. *Guidance on the legal definition of waste and its application.* Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/69590/pb13813-waste-legal-def-guide.pdf (Accessed: 31/05/2019).

[83]https://leanconstruction.org.uk/wp-content/uploads/2018/09/C730-Lean-tools-hi.pdf (Accessed: 17/06/2019).

[84] Caldera, H.T.S., Desha, C. and Dawes, L., 2017. Exploring the role of lean thinking in sustainable business practice: A systematic literature review. *Journal of Cleaner Production*, 167, pp.1546-1565.

- ***Motion:*** Waste in motion includes any unnecessary movement of people, equipment, plant or materials. This includes walking, lifting, reaching, bending, stretching, and moving.
- ***Correction or defects:*** Defects result from work carried out incorrectly the first time. They must be repaired, sorted, re-made, or re-worked.
- ***Transportation:*** Transportation waste is unnecessary movement of materials that does not directly supporting value adding activities. Measuring transport waste is site specific: sub-optimal site layouts can cause significant transportation waste.
- ***Inventory:*** Excess inventory includes resources purchased before they are needed or in excess of those required for the job, work-in-process and finished goods. Excess inventory can be caused by over-purchasing of material and goods or producing houses before customers are prepared to pay for them.
- ***Overproduction*****:** Overproduction occurs when more or better output than is needed is produced. It occurs when an activity is completed to a higher standard than required, faster than scheduled or before the next task in the sequence is ready to start.
- **Over-processing:** Over-processing refers to doing more work, adding more components, or having more steps in the process than are required by the customer. Examples of over-processing are double handling and checking.

An example of the lean construction tool could be used to facilitate achieving onsite a good construction efficiency including value stream mapping (VSM), just-in-time (JIT), pull production, 5S/7S, kaizen, visual control, and last planner can facilitate achieving onsite construction efficiency[85].

The primary step in mapping the construction process is the identification of which activities in the process add value and which do not[8]. Once the classification of these categories is done, it is then possible to implement the action by improving performance in the value-add activities, reducing as much as possible the supporting activities and eliminating wastes.

3.7.2 Process efficiency metrics

From the foregoing discussion, it is clear that if efficiency is defined in terms of waste, it will need to be measured in a number of ways, many of which have been described in previous sections, many of which will be measured in different units. Whilst this might be useful for determining where improvements in efficiency may be made, it does not provide a single measure of efficiency. However, if we return to our original definition of efficiency, “producing more for less”, ultimately for all the AIMCH partners this means producing more value at lower cost.

[85] Ansah, R.H., Sorooshian, S., Mustafa, S.B. and Duvvuru, G., 2016, September. Lean construction tools. In *Proceedings of the 2016 International Conference on Industrial Engineering and Operations Management*, Detroit, Michigan, USA.

3.7.3 Margin or surplus

Value - cost	
Method of measurement	Margin is expressed as the following percentage. $$Margin = \frac{Value - Cost}{Value} \times 100$$ For Barratt, Stewart Milne, Tarmac and Forster, value is simply turnover, and the metric is one that will be readily available. L&Q may wish to include social value in the equation, but this can be extremely difficult to measure.
Merits	• Simple, meaningful, objective, cost-effective, verifiable, widely understood and used.
Disadvantages	• Provides no clues as to the causes of changes in efficiency. However, these may be identified from metrics recommended in previous sections of this report.
Use	• Widely used and reported.

3.7.4 Summary

There is considerable confusion in the literature as to how efficiency is defined. However, in this report it is defined in terms of waste. Many of the metrics described in previous sections can be used to measure waste, but each is only a partial measure of efficiency and may be measured in different units.

3.7.5 Conclusions and recommendations

We conclude that there is no unique, comprehensive and generally accepted metric describing efficiency. We therefore suggest that metrics describing wastage in labour, plant, material and finance are developed on a case by case basis taking inspiration from sectors such as manufacturing where, for example, the efficiency of a plant is often described by the so called “down time”. When no other viable option is available, we suggest the adoption of percentage margin as an umbrella metric for efficiency whilst recognising that it is also a measure of ‘efficiency’ of the whole process including for instance sales and marketing.

3.8. MATERIAL WASTE

3.8.1 Preamble

In this report, waste including material waste is defined as '*anything that does not add value for the client*'. This includes all the material that is delivered to a site but which is not used for the purpose for which it was purchased and, as a consequence is discarded, is intended to be discarded or is required to be discarded[86]. This definition has been chosen because although a material can be reused on site for purposes other than the ones for which it was originally bought, this possibility implies either inefficiencies in the supply/construction process, or product quality issues, or a combination of both.

A graphical representation of the waste hierarchy and of the actions associated with each level is shown in Figure 3.

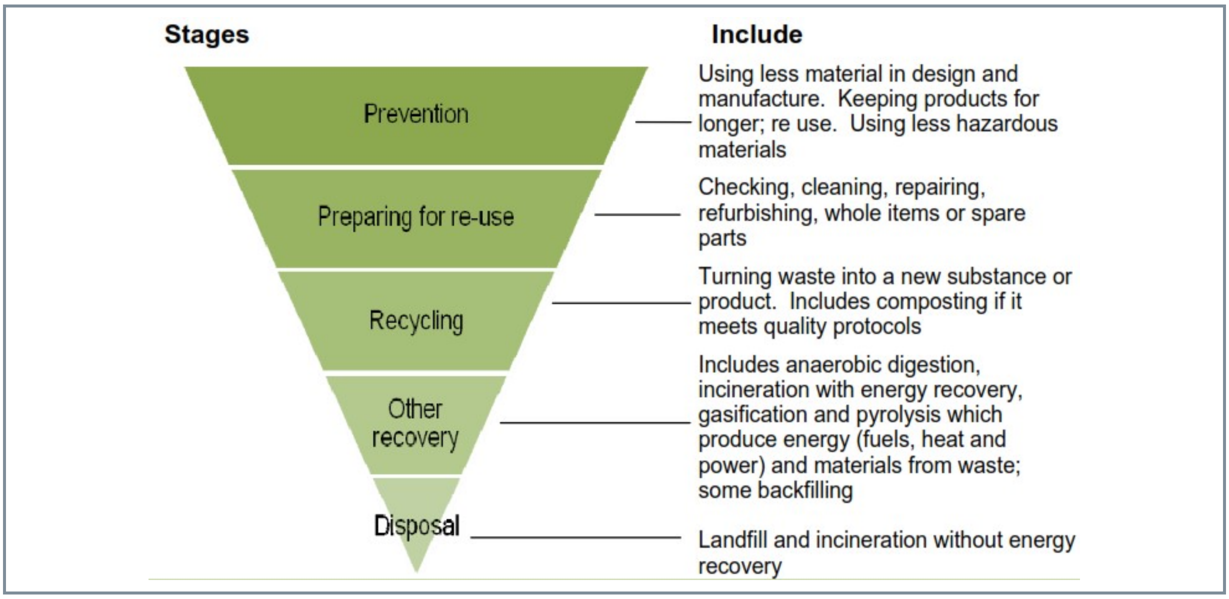

Figure 3. Waste hierarchy according to Defra (2011)[87]

The first step in assessing the performance of a company and/or a project in terms of material waste is to determine when material waste is generated and if the waste produced is part of the performance assessment or not. This can be done by defining the life cycle of the materials (and components) that are of interest. As shown in Figure 4 and Figure 5, four types of component/material life cycles can be defined at a very high level in the construction sector. These four cycles can be defined as follow.

- **Cradle-to-gate:** Captures the life cycle of a component from the moment the raw materials are extracted/sourced until the end of the manufacturing process which results in the component itself. Waste is generated as a result of the manufacturing process.
- **Cradle-to-complete construction cycle**: Captures the life cycle of a component from the moment the raw materials are extracted/sourced until the end of the on-site construction phase during which it is used. Waste is generated both during the manufacturing process and the on-site construction phase.
- **Cradle-to-grave cycle**: Encompasses the life cycle of a component from the moment the raw materials are extracted/sourced until the asset in which the component was used is demolished (ie until the end of life of the asset) and the resulting waste is treated and disposed. This cycle includes intermediate steps such as the on-site construction phase, and the operational phase (eg repair, replacement). Waste is produced during each of these phases.

[86] Defra, 2012. *Guidance on the legal definition of waste and its application.* Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/69590/pb13813-waste-legal-def-guide.pdf (Accessed: 31/05/2019).

[87] Defra, 2011. *Guidance on applying the Waste Hierarchy.* Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/69403/pb13530-waste-hierarchy-guidance.pdf (Accessed: 23/05/2019).

- **Cradle-to-cradle cycle**: Captures the life cycle of a component from the moment the raw materials are extracted/sourced until the component itself is recycled and converted into a new product at the end of its life. Even in this case, waste may be produced at any intermediate step.

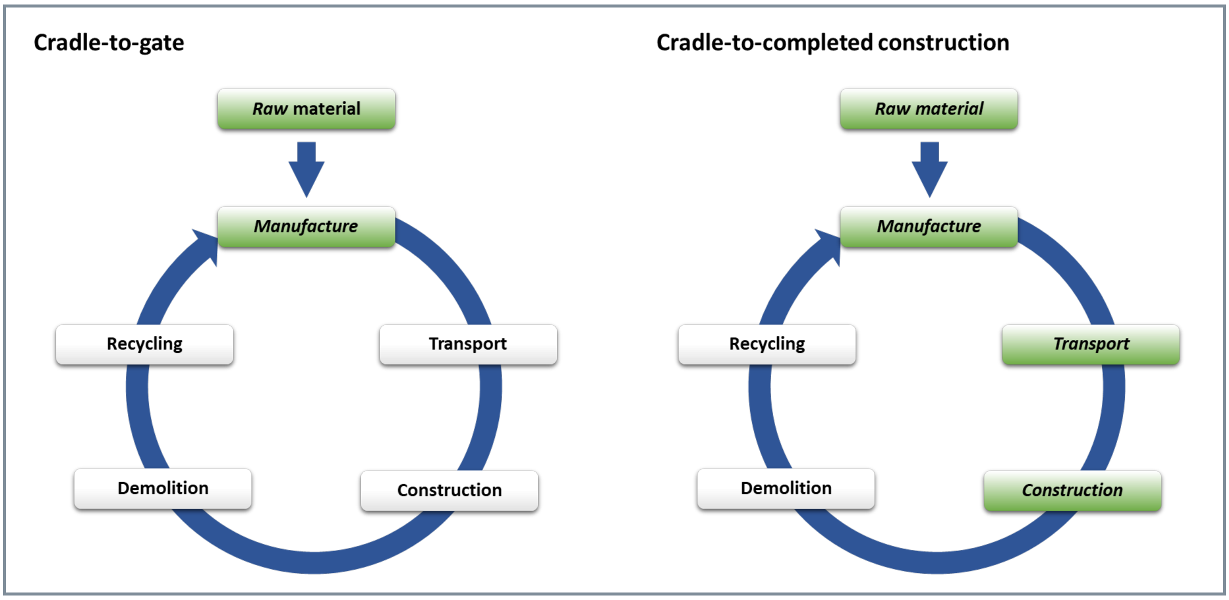

Figure 4. Cradle-to gate and cradle-to-completed construction cycles (after UKGBC, 2015[88])

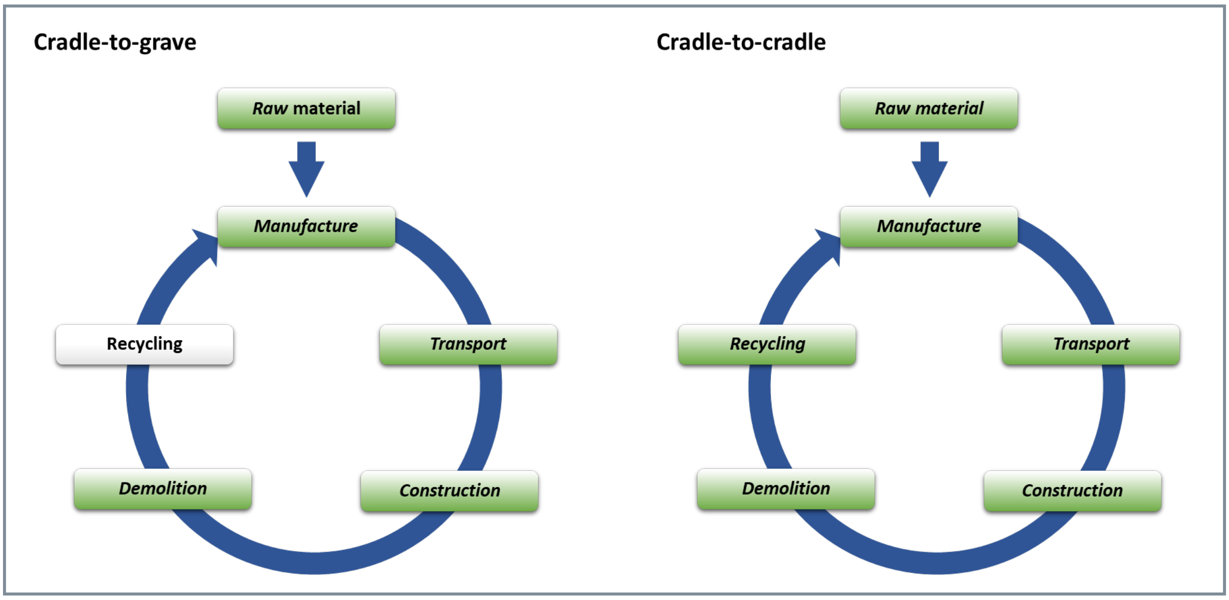

Figure 5. Cradle-to-grave and cradle-to-cradle cycles (after UKGBC, 2015[89])

Details of how material waste is produced, and either reused, recycled and disposed material during different life cycle stages are summarised in Figure 6.

[88] UK Green Building Council (UKGBC), 2015. Tackling embodied carbon in buildings. Available at: https://www.ukgbc.org/sites/default/files/Tackling%20embodied%20carbon%20in%20buildings.pdf (Accessed: 21/05/2019).

[89] UK Green Building Council (UKGBC), 2015. Tackling embodied carbon in buildings. Available at: https://www.ukgbc.org/sites/default/files/Tackling%20embodied%20carbon%20in%20buildings.pdf (Accessed: 21/05/2019).

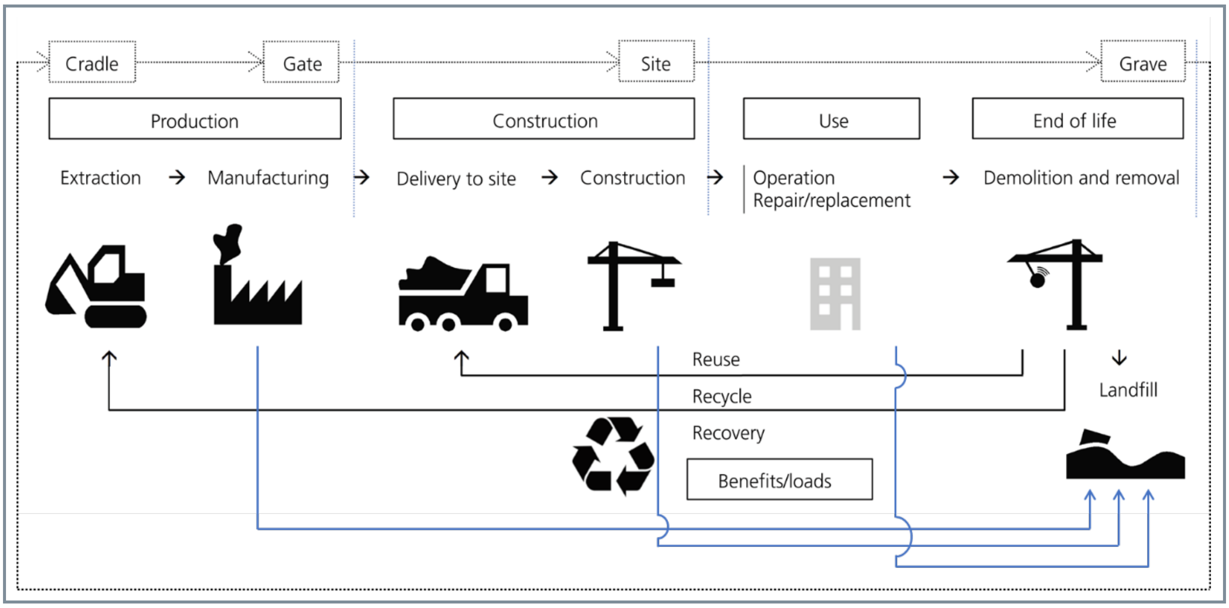

Figure 6. Life cycle stages and material waste generation associated to each one of their phases (modified from De wolf et al., 2015)[90]

Based on the schematic proposed in Figure 4 to Figure 6, a series of additional cycles can be defined by considering different milestones (eg a gate-to- to-complete construction cycle, a gate-to-grave cycle, etc.). It should be noted that because each cycle has different boundaries, a metric describing material waste generation (or performance) in a given cycle might not be appropriate for another one. For example, a hypothetical metric "*percentage of waste for reuse*" might be appropriate if the construction phase and the demolition phase are included in the life cycle, but it might be of less importance if they are excluded. In reflecting the strategic objectives of the AIMCH partners, this literature review focussed in particular on those metrics appropriate for describing material waste generation within the gate-to-complete construction cycle.

3.8.2 Data collection and material waste indicators

By applying the classification proposed by BRE SMARTWaste[91], two types of indicators connected to material waste can be mainly found in the literature: those which can be categorized as Environmental Performance Indicators (EPI) and those which are described as Key Performance Indicators. The former establish a relationship between the amount of produced material waste and a project-related physical quantity such as, for example, m^2 of floor area; the latter describe the amount of waste produced per 'unit' of construction costs (eg per £100k). Both these indicators are sometimes identified as Waste Generation Rates (WGRs)[92,93].

Data collection in terms of material waste is often enforced by local authorities and/or by the necessity of achieving environmental certifications (eg BREAM). Under such circumstances, companies are usually required to outline and adopt a Site Waste Management Plan (SWMP)[94] which involves the use of standardised forms for data collection. As a result, most of the material waste-related indicators can be calculated with no additional effort from the company's perspective.

In order to improve the performance of a company in terms of material waste (ie in order to minimise waste), the causes underlying its generation must first be identified. Accordingly, we suggest that those metrics that seek not

[90] De Wolf, C., Yang, F., Cox, D., Charlson, A., Hattan, A.S. and Ochsendorf, J., 2016, August. Material quantities and embodied carbon dioxide in structures. In *Proceedings of the Institution of Civil Engineers-Engineering Sustainability* (Vol. 169, No. 4, pp. 150-161). Thomas Telford Ltd.

[91] CRW (Construction Resources & Waste Platform), 2009. *Refurbishment waste benchmarking report.* Available at: http://www.wrap.org.uk/sites/files/wrap/Refurbishment-waste-benchmarking-report.pdf (Accessed: 05/04/2019).

[92] Wu, Z., Ann, T.W., Shen, L. and Liu, G., 2014. Quantifying construction and demolition waste: An analytical review. *Waste Management*, *34*(9), pp.1683-1692.

[93] Lu, W., Chen, X., Peng, Y. and Shen, L., 2015. Benchmarking construction waste management performance using big data. *Resources, Conservation and Recycling*, *105*, pp.49-58.

[94] http://www.netregs.org.uk/media/1119/a-simple-guide-to-site-waste-management-plans.pdf (Accessed: 05/04/2019).

only to quantify the waste but also to associate it to a given source should be preferred to other, more generic indicators.

The material waste metrics we identified are as follow.

- Volume of waste/100 m^2 or/plot
- Weight of waste/100 m^2 or/plot
- Volume of waste/£100k
- Weight of waste/£100k
- Percentage of segregated material waste
- Amount of material waste to landfill
- Amount of material diverted from landfill
- Percentage waste
- Net waste
- Tonnes/£m revenue

Details of the metrics whose use we recommend are provided below: details of the remaining metrics are provided in Appendix E.7.

3.8.3 Net waste

Net waste	
Method of measurement	This metric is defined as the difference between the 'value of materials not incorporated in the construction works' and the 'value of additional recovered materials incorporated in the construction works or in off-site applications' which includes 'materials reused on site, recycled content above baseline practice for manufactured building products, use of reclaimed products, and the value of materials reclaimed for use off-site'.[95] This metric has been suggested by WRAP (Waste and Resources Action Programme).
Merits	• Reflects strategic objectives. • Objective, verifiable. • Holistic approach covering aspects such as waste reduction and recycling. • Allows the identification of improvement opportunities. • Provides value and cost information. • Allows the identification of changes that are more likely to have the greatest impact if implemented. • A free of charge online tool based on Net waste is available through the WRAP website[96].
Disadvantages	• Has to be calculated at the project level. • Is built around the concept of continuous improvement so there is no fixed target to reach. • Involves a cultural change of all the stakeholders involved in the design and construction phase. An improvement of this indicator can be obtained by optimising the design and the delivery of the project, and not simply changing the materials used. • Data on both material entering and leaving the site must be collected.
Use	• It is mainly used by WRAP NW Tool[97] users. Examples of property developers using this metric can be found too (eg Crest Nicholson[98]).

3.8.4 Software and online tools for measuring material waste indicators

Numerous software and online tools are available that allow the material waste performance of a company to be measured. Most of them (e.g. BRE SMARTWaste, WRAP Net Waste Tool) have been captured in the literature review carried out by Akinade et al. (2016[99], 2018[100]). The authors identified 32 different studies and tools dealing with waste management (see Figure 7), and they categorized them in five functional groups. It should be noted that not all the listed tools are currently commercialized: some of them (eg the combined used of bar codes and GPS-GIS Technology by Li et al., 2005[101]) have only been used in action-based research. Moreover, not all the items are actually independent tools: some of them are sub-components of more comprehensive ones. For example, SMARTAudit is part of the SMARTWaste suite[102]; SMARTStart too.[103]

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95 WRAP. *A metric for the construction sector. The Net Waste Method – testing a new standard for measuring waste neutrality* Available at: http://www.wrap.org.uk/sites/files/wrap/Net%20Waste%20Brochure.pdf (Accessed: 21/05/2019).

96 http://nwtool.wrap.org.uk/ToolHome.aspx (Accessed: 21/05/2019).

97 WRAP, 2012. *Net Waste Tool. User Guide, Version 1.0.* Available at: http://nwtool.wrap.org.uk/Documents/NW%20Tool%20Manual.pdf (Accessed: 21/05/2019).

98 https://www.crestnicholson.com/about-us/integrating-sustainability/our-data (Accessed: 21/05/2019).

99 Akinade, O.O., Oyedele, L.O., Munir, K., Bilal, M., Ajayi, S.O., Owolabi, H.A., Alaka, H.A. and Bello, S.A., 2016. Evaluation criteria for construction waste management tools: towards a holistic BIM framework. *International Journal of Sustainable Building Technology and Urban Development*, *7*(1), pp.3-21.

100 Akinade, O.O., Oyedele, L.O., Ajayi, S.O., Bilal, M., Alaka, H.A., Owolabi, H.A. and Arawomo, O.O., 2018. Designing out construction waste using BIM technology: Stakeholders' expectations for industry deployment. *Journal of cleaner production*, *180*, pp.375-385.

101 Li, H., Chen, Z., Yong, L. and Kong, S.C., 2005. Application of integrated GPS and GIS technology for reducing construction waste and improving construction efficiency. *Automation in Construction*, *14*(3), pp.323-331.

102 https://www.bre.co.uk/calibre (Accessed: 27/05/2019)

103 http://www.smartwaste.co.uk/smartstart/about.jsp (Accessed: 27/05/2019).

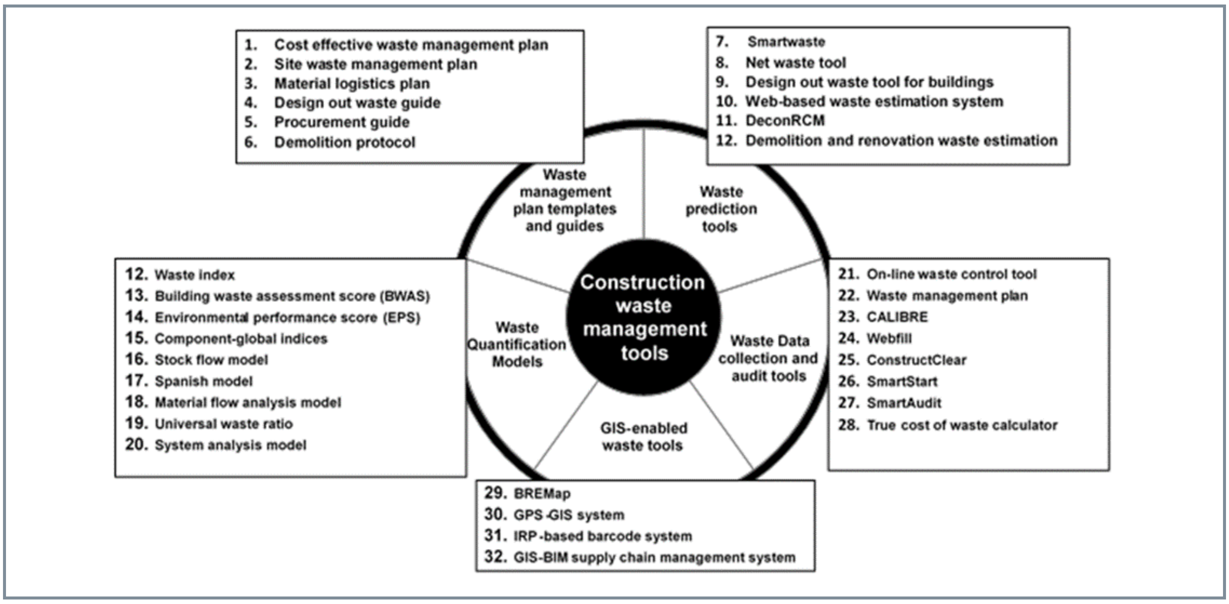

Figure 7. Graph showing the 32 tools for waste management identified by Akinade et al. (2016)[99].

3.8.5 Summary

A variety of different metrics for materials waste are in regular use. Some are more complex than others. Each measure slightly different aspects of waste, so in the context of this report, it is necessary to be absolutely clear about the strategic objectives and to choose metrics which most closely reflect them cost-effectively. The units of measurement depend on the type of waste. If volume is used, consideration needs to be given to the volume of enclosed air. Consideration also needs to be given to the degree of subjectivity that may be required.

3.8.6 Conclusions and recommendations

In our view, the most relevant, generic and simplest metric to calculate is the net waste as described in Section 3.8.3. If the intention is to eliminate waste entirely in the recognition that recycling and re-use have costs associated with them, this metric is directly relevant. At the same time, it can be used for particular types of materials, for particular elements of construction, or across the whole company.

We are conscious that this is not the method currently preferred by the partners, but would like to test the appetite for using it in conjunction with the current metrics.

4. OVERALL SUMMARY

This report presents a comprehensive review of the literature associated with the following metrics.

- Safety
- Productivity
- Quality
- Cost
- Time
- Predictability
- Efficiency
- Material waste

It also covers emerging technologies that may have future application in performance measurement.

Whilst the importance of life cycle costs and sustainability, particularly carbon emissions, was recognised, the lack of data militates against consideration of the former, whilst the partners intend to give separate consideration to the latter.

The summary that follows is a copy of that provided at the beginning of this report. It is repeated here for convenience.

4.1. SAFETY

The following metrics were reviewed.

Leading

- Number of safety observations (over a given period)
- Percentage of negative randomly performed drug and alcohol tests
- Number of times work has been stopped due to safety breaches
- Percentage of audited items in compliance
- Percentage of tasks which are planned in advanced
- Percentage of orientation events attended by the owner's project manager

Lagging

- Incidence rates
- Frequency rates
- Severity rate

Based on our review of the literature, we recommend the use of two leading metrics: percentage of audited items in compliance and percentage of tasks which are pre-planned. We also recommend the use of one lagging metric: frequency rates, and in particular, number of days of lost work per 100,000 hours worked.

We further recommend that consideration should be given to supplementing this metric with the number of near misses recorded per 100,000 hours worked.

4.2. PRODUCTIVITY

The following metrics were reviewed.

- Gross value added/number of jobs
- Gross value added/total hours worked
- Gross value added/labour cost
- Value of work completed/total hours worked
- Value of work completed/labour cost

- Labour hours per plot
- Output of physical units/total hours paid
- Output of physical units/available hours worked
- Output of physical units/productive hours worked
- Delays
- Earned value/Actual cost
- Earned hours/Actual hours
- Construction Industry Institute Construction Performance Assessment

Where different methods of measurement were possible, these were also reviewed.

Our recommendations are as follows.

If detailed information about the process of construction, its context and constraints is required, and if the labour force cannot be used to keep the necessary records, then direct, continuous observation by a trained observer should be used.

If the purpose is simply to determine the reduction in labour inputs occasioned by off-site manufacture, then the use of RFID or BLE should be piloted after suitable investigation of any constraints or shortcomings that might arise. In any case, it would be advantageous, not only to the AIMCH project but to the whole industry if RFID were supplemented by direct observations and activity sampling so the relative merits of each approach could be determined in more depth.

4.3. QUALITY

The following metrics were reviewed.

- HBF star rating
- Field Rework Index
- ISO 9001 Accreditation
- Yield (ratio of number of non-defective items to total number of items manufactured)
- Quality rating ($\frac{Total\ construction\ capital\ cost - Cost\ of\ post\ occupation\ defects}{Total\ construction\ capital\ cost}$)
- Costs due to error/total construction cost
- Number of reportable items
- Number and type of items that did not pass visual inspection

For Barratt, and L&Q, the HBF star rating and the number of reportable items are widely recognised, objective, mature, relate closely to strategic objectives and are easily administered so we recommend that their use should be continued. For similar reasons, and because its use is suggested by CLC, we recommend that the NHBC quality rating should also be used by Barratt, L&Q, and Tarmac. In addition, we recommend that Forster Roofing should continue to use the number of reportable items as a measure of quality,

4.4. COST

The following metrics were reviewed.

- Average construction cost/m^2 (GIFA)
- Construction cost/bedroom
- Average construction cost/plot
- Construction cost/item or element
- Cost variance
- Change in cost of construction
- Cost of rectifying defects

- Prelims cost/capital cost
- Cost growth (%)
- Phase cost ratio
- citiBLOC/m^2 (a citiBLOC is the average price of a basket of '*representative construction items'*

To satisfy the principal strategic objective for Barratt and L&Q, we recommend that the principal metrics should be the average construction cost per plot and the average cost of rectification of defects per plot. Costs should exclude the costs of foundations, which are assumed to be the same for conventional and OSM, but should include the costs of prelims which may vary between conventional and off-site construction. The costs of solutions using off-site manufacture should include the costs of investment in the necessary facilities, design of bespoke solutions, manufacturing, logistics and assembly. Clearly, costs will have to be compared on plots of similar characteristics in terms of quality and functional specification eg two bedroom terraced social housing.

To compare the costs of individual elements (eg walls roofs, etc.), it will be necessary to collect construction costs related solely to those elements. Of these, the most difficult will be labour hours and preliminaries (eg additional cranage or reduction in use of forklift to deliver materials). To accomplish this, it may well be necessary to carry out direct observations.

4.5. TIME

The following metrics were reviewed.

- Overall time (or programme duration)
- Time/output of physical units
- Time per plot
- Time/m^2
- Delivery speed
- Change in time for construction
- Projects schedule variation (%)
- Schedule growth (%)
- Project schedule factor ($\frac{Actual\ total\ project\ duration}{Initial\ predicted\ project\ duration+Duration\ of\ approved\ changes}$)

In satisfying the principal strategic objectives of Barratt and L&Q, the average elapsed construction time per plot is the metric of interest, since this defines when a house will be ready for the customer. Moreover, this metric can be easily converted in the elapsed time per m^2 whose use has been suggested by CLC (see Section E.5.2 for more details on the use of this metric). As with costs, times will have to be compared on plots of similar characteristics in terms of quality and functional specification. Additionally, because urgency is driven by demand, it will be necessary to ensure that that build contexts are comparable too if comparisons between on-site and off-site construction are to be meaningful. To achieve this, it may be necessary to compare both average and minimum construction times. Again, we recommend that the time to construct foundations is excluded since these will be more or less the same for on- and off-site construction. For off-site construction, consideration will have to be given to any time required for bespoke design, for manufacture, and for transportation as well as assembly on site. We recommend that the time taken for each of these phases is recorded.

For Tarmac, Stewart Milne and Forster Roofing, the time required to construct the relevant elements is the focus of attention. It will therefore be necessary to record the start and completion times of each relevant activity. This may be achieved by the operatives themselves, by supervisors or by intermittent or continuous observations by an independent observer.

4.6. PREDICTABILITY

The following metrics were reviewed.

- Time predictability – change in completion date
- Time predictability – average percentage overrun
- Cost predictability

- Cost and time predictability – SmartSite KPIs
- Safety, productivity, quality and material waste predictability

In the light of the AIMCH partners' strategic objectives, and in the pursuit of simplicity and consistency we recommend that time and cost predictability should both be measured in terms of the average percentage overrun. For complete houses, it should be measured at the plot level (ie average percentage overrun per plot). It can however be measured in the same way for any element or activity in the construction process eg walls, floors or roofs.

4.7. EFFICIENCY

Efficiency was defined as doing more with less. A process is efficient if waste is minimised ie if maximum output is produced by a minimum of resource. The many ways of measuring waste wherever it occurs in the process are best expressed in the context of lean thinking. Since these are generally only partial measures of efficiency in terms of our definition, we conclude that there is no unique, comprehensive and generally accepted metric describing efficiency. We therefore suggest that metrics describing wastage in labour, plant, material and finance are developed on a case by case basis taking inspiration from sectors such as manufacturing where, for example, the efficiency of a plant is often described by the so called "down time". When no other viable option is available, we suggest the adoption of percentage margin as an umbrella metric for efficiency whilst recognising that it is also a measure of 'efficiency' of the whole process including for instance sales and marketing.

4.8. MATERIAL WASTE

The following metrics were reviewed.

- Volume of waste/100m^2 or /plot
- Weight of waste/100m^2 or /plot
- Volume of waste/£100k
- Weight of waste/£100k
- Percentage of segregated material waste
- Amount of material waste to landfill
- Amount of material diverted from landfill
- Percentage waste
- Net waste
- Tonnes/£m revenue

In our view, the most relevant metric to calculate is the net waste measured as the difference between the 'value of materials not incorporated in the construction works' and the 'value of additional recovered materials incorporated in the construction works or in off-site applications'. If the intention is to eliminate waste entirely in the recognition that recycling and re-use have costs associated with them, this metric is directly relevant. At the same time, it can be used for particular types of materials, for particular elements of construction, or across the whole company. We are conscious that this is not the method currently preferred by the partners, but would like to test the appetite for using it in conjunction with the current metrics.

5. OVERALL CONCLUSIONS AND RECOMMENDATIONS

The choice of metric is critically dependent on the strategic objectives. Since different AIMCH partners have different objectives, it is unlikely that a single set of metrics will satisfy all partners. Nevertheless, the results of the literature review and analysis we have undertaken provide comprehensive evidence on which to base decisions about which metric should be used in which circumstance.

We recommend that each partner carefully reviews the recommendations we have made together with the underlying rationale, and checks that the metrics proposed satisfy both their strategic objectives and any internal constraints that may apply.

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APPENDIX C GLOSSARY OF TERMS

C.1. Introduction

At the induction meeting on 29 March, it was recognized that there was value in developing a common vocabulary so that all stakeholders could have a shared understanding of the need, the deliverables and the outputs from this research project. The University of Dundee (UoD) team undertook to produce a glossary of terms to be used throughout the research commission for WP2.

The following Glossary seeks to provide unambiguous definitions of the terms that are most likely to be used frequently during the project, and which might potentially give rise to confusion. In general, definitions are context dependent. The context of the definitions below is WP2 of the AIMCH project – "Productivity Mapping and Literature Review".

It is also recognized that different organisations use different vocabularies. This Glossary is not meant to supersede those internal vocabularies, but is simply the vocabulary that is to be used in the context of this research project.

Where a defined term is used in the text, it appears in bold.

C.2. Definitions

Cost is the amount of money used to produce something or deliver a service. It should be distinguished from "price" which is the amount of money that a client pays for goods or services.

Cost effectiveness is the extent to which a product or process delivers **value** for money.

Defects are faults. For the purposes of his commission, they relate to faults in the finished product, though elsewhere, they may include faults in a process.

Efficiency is doing more with less. A process is efficient if **waste** is minimised ie if maximum output is produced. by a minimum of resource.

Gaps in the context of this commission have two connotations. The first relates to gaps in the performance indicators or metrics that have already been identified. They answer the question: "Have we omitted to include a metric that should be included?". The second relates to gaps in the availability, **reliability** or **robustness** of tools to measure the performance indicators that have been identified.

Labour productivity is the amount of output per unit of input. It can be measured in a number of ways including eg m3 of concrete or value of concrete produced per person hour or cost of labour.

Output is the amount of work produced. It is most often measured in terms of physical units or value.

Performance relates to the extent to which a product, project, process or system meets the functional criteria for which it was designed. It often has more than one component (eg cost, quality, safety) ie it is multi-dimensional.

Predictability reflects the confidence associated with an assertion concerning future **performance**.

Productive describes a rate of producing **output**. Thus, a gang may be considered productive if it produces 40m^2 of brickwork in a day. A site may be considered productive if it produces work to a value of £10m a month. It differs from productivity because the input is not quantified.

Productivity is the ratio of output to input. Both outputs and inputs may be measured in different ways. For example, output may be measured in terms of m^2 of formwork, or value of work produced. Equally, input may be measured in different ways eg labour (cost or hours), plant (cost or hours), material (cost or quantity), investment (cost). Sometimes more than one input may be considered. This is called multi-factor productivity. Labour productivity, with which this commission is principally concerned, is known as single factor productivity.

Protocol in this context means the rules governing the way in which performance indicators should be measured.

Quality is the extent to which work meets or exceeds the specification.

Reliability is defined differently depending on the context. The **reliability** of a product or process is the ability of that product or process to perform a required function under stated conditions for a stated time. The **reliability** of a tool or method of measurement is the degree to which the result of a measurement or calculation can be depended on to be accurate. It is the degree to which a measurement gives the same results each time that it is carried out, assuming that the underlying thing being measured does not change.

Rework is work that is executed more than once.

Robustness is the extent to which a product or process can continue to fulfil its function under adverse conditions.

Waste is anything that does not add value for the client.

APPENDIX D CRITERIA FOR ASSESSING PERFORMANCE METRICS

D.1. Introduction

At the induction meeting on 29 March, it was agreed that it would be useful to develop a set of criteria against which the relative merits of different performance indicators could be assessed. The University of Dundee team agreed to produce a list and circulate for comment. It was also suggested that the criteria should be weighted in proportion to their relative perceived importance.

The AIMCH partners are invited to comment on, add to or delete from this list, and to give each criterion a mark out of ten reflecting its relative importance to their own organisation. It is recognised that different organisations may assign different weights to the criteria, which may lead to different preferred indicators in each organisation.

D.2. Criteria

Criterion	Weight (Mark out of 10)
Relate to strategic objectives	
Drive effective decisions and process improvements	
Meaningful to users	
Simple, unambiguous and understandable	
Measurable objectively	
Cost-effective	
Timely	
Reliable and consistent	
Verifiable	

APPENDIX E ADDITIONAL METRICS

E.1. Safety

E.1.1 Leading metrics – Number of safety observations (over a given period)

Number of safety observations (over a given period)	
Method of measurement	The number of safety observation carried out in a given period can be extracted from the company's Health and Safety Management System or other sources. To be effective, it is suggested that a large proportion of the on-site workforce is trained to carried out observations[104] and that time is dedicated to data collection and processing.
Merits	• Simple, easy to measure, reliable. • Can result in a behavioural change in the workforce.
Disadvantages	• Provides no information about the type or frequency of unsafe practices. • Does not readily relate to strategic objectives. • If not supported by an observation plan, it can be subjected to bias: the observer might focus on specific areas or aspects and neglect others. • To be effective, the safety plan must also be adopted by sub-contractors.
Use	• Due to its simplicity, it is used by the industry (eg Mace[105]).

[104] Hallowell, M.R., Hinze, J.W., Baud, K.C. and Wehle, A., 2013. Proactive construction safety control: Measuring, monitoring, and responding to safety leading indicators. *Journal of Construction Engineering and Management, 139(10),* p.04013010.

[105] Mace, 2018. https://www.macegroup.com/about-us/financial-performance (Accessed: 10/05/2019).

E.1.2 Leading metric – Percentage of negative randomly performed drug and alcohol tests

Percentage of negative randomly performed drug and alcohol tests	
Method of measurement	This is the percentage of negative random drug or alcohol results in a population of observations. It is a leading indicator that can be subject to changes in a short period[106] and is hence considered a reliable indicator of the situation at the moment data are collected. A study published in 2001[107] suggested that reductions of up to 51% in number of injuries can be achieved within two years from the implementation of the metric[108].
Merits	• Provides timely information. • Allows prompt implementation of mitigation measures (eg asking a person to leave the site). • Effective way to identify potential people at risk and to adopt ad-hoc safety measures. • Can induce positive behavioural changes in the workforce. • Benefits in terms of safety performance are intrinsic to the procedure adopted for collecting data.
Disadvantages	• Very limited in the safety issues addressed so does not address strategic objectives. • Costs associated with collecting and processing the samples. • If carried out too frequently, it might be seen as an invasion of the privacy by the workforce. • It requires employee consent in order to be incorporated in an existing contract of employment[109].
Use	• Examples of companies adopting this indicator can be found in the literature (eg Barratt Development Plc[110]). Purpose designed testing services for the construction sector are available from medical diagnostic providers (eg AlphaBiolabs[111], Synlab[112]).

[106] Jazayeri, E. and Dadi, G.B., 2017. Construction safety management systems and methods of safety performance measurement: A review. *Journal of Safety Engineering, 6(2),* pp.15-28

[107] Gerber, J.K. and Yacoubian Jr, G.S., 2001. Evaluation of drug testing in the workplace: study of the construction industry. *Journal of Construction Engineering and Management*, *127*(6), pp.438-444.

[108] https://www.hsimagazine.com/article/substance-misuse-and-drug-testing-in-the-construction-industry (Accessed: 14/05/2019).

[109] https://www.dnalegal.com/blog/drug-and-alcohol-testing-workplace-what-are-your-rights (Accessed: 14/05/2019).

[110] https://www.barrattcommercialsupport.co.uk/news/2017/02/drug-and-alcohol-testing (Accessed: 14/05/2019).

[111] https://www.alphabiolabs.co.uk/workplace-testing-sectors/the-construction-industry-drug-and-alcohol-testing/ (Accessed: 14/05/2019).

[112] https://www.synlab.co.uk/drug-and-alcohol-testing/what-do-i-need/construction/ (Accessed: 14/05/2019).

E.1.3 Leading metric – Number of times work has been stopped due to safety breaches

Number of times work has been stopped due to safety breaches	
Method of measurement	Introduction of this metric requires a Stop-Work Authority (SWA) programme to be in place. The SWA defines the framework describing when, who and how SWA should be enacted. Although it is often presented as the ratio between the number of times work on a site has been halted and a given number of worked hours (eg 200,000), it is considered a leading indicator. It allows information on the effectiveness of the Safety Management System, the machine/tool inspection and maintenance systems to be inferred.
Merits	• Requires the company to apply a SWA approach; this means the direct involvement of the on-site workforce. • Relates to strategic objectives. • It is a leading indicator and does not require purpose collected data.
Disadvantages	• Initial training is expensive. • Subject to bias. • Might be of limited usefulness if not substantiated by additional information on the causes that led to the halt of work. • Major obstacle in the use of SWA (and conversely in the reliability of this metric) have been identified as "peer pressure and fear of angering supervisors".[113]
Use	• Off-shore Oil and Gas Industry[114,115,116]; Construction industry in US.[117,118]

[113] https://www.safetyandhealthmagazine.com/articles/17242-stop-work-authority (Accessed: 16/05/2019).

[114] Witter, R.Z., Tenney, L., Clark, S. and Newman, L.S., 2014. Occupational exposures in the oil and gas extraction industry: State of the science and research recommendations. *American journal of industrial medicine, 57(7),* pp.847-856.

[115] https://www.deepwater.com/Documents/15.a.2.-Stop%20Work%20Authority%20Status-01.10.14.pdf (Accessed: 16/05/2019).

[116] https://www.offshore-mag.com/regional-reports/article/16757299/swa-is-an-accepted-building-block-in-safety-and-emergency-management (Accessed: 16/05/2019)

[117] https://www.pecsafety.com/safetymeetings/SWA-SM-ALL-IN-ONE.pdf (Accessed: 16/05/2019).

[118] https://www.ghd.com/en-us/resourcesGeneral/Documents/GHD-SOP-HSE-069-Stop-Work-Authority.pdf (Accessed: 16/05/2019).

E.1.4 Leading metric – Percentage of orientation events attended by the owner's project manager

Percentage of orientations events attended by the owner's project manager	
Method of measurement	Defined as the percentage of orientation sessions on a site in which the owner's project manager has actively participated.[119]
Merits	• Simple, objective reasonably cost-effective and verifiable. • Beneficial impact on the workforce: it helps reduce the perception that safety is a tick box exercise and helps to establish an attitude toward safety.[119]
Disadvantages	• An indirect measure of the owner/top management involvement and commitment so isn't directly related to strategic objectives. • Does not measure the quality of the events or the benefits realised.
Use	• The validity and the process that led to the development of this metric can be found in research papers – mostly referable to US researches – but its adoption by the industry is not documented.

[119] Liu, H., Jazayeri, E. and Dadi, G.B., 2017. Establishing the influence of owner practices on construction safety in an operational excellence model https://www.networkrail.co.uk/who-we-are/how-we-work/performance/safety-performance/workforce-safety/, 143(6), p.04017005.

E.1.5 Lagging metric – Incidence rates

Incidence rates	
Method of measurement	Incidence rates are lagging indicators describing the lack of safety in terms of number of events (whether they are accidents, near-misses or days of lost work) per number of employees over a period usually spanning over one year. The Injury Incidence Rate defined by the Health and Safety Executive[120] (HSE) is an example of incidence rate describing the number of reported injuries per 100,000 employees. Further incidence rates can be obtained opportunely normalised against a variety of parameters which may be chosen based on the purpose of the measurement. The following list of lagging indicators that can be used to produce alternative incidence rates was developed by HSE[121] within the "Leadership and worker involvement toolkit" framework. • Total number of accidents and incidents (fatal and nonfatal); • Total number of near misses; • Total number of days lost due to injury or work-related illnesses; and • Number of overdue action items over a given period (eg 6 or 12 months). Resources required to correctly capture these lagging indicators are: standardised forms, personnel available to input and analyse data[122].
Merits	• Directly related to strategic objectives. • Easily calculated from statutory records, widely understood, cost-effective, objective, reliable mature and verifiable. • Benchmarks available at national and regional level from HSE statistical data (eg RIDIND, RIDDOR).
Disadvantages	• As lagging indicators, incidence rates describe the lack of safety which characterises a given sector (or company) in the past. No information on the current situation can be inferred. • Under-reporting can occur when the normalised indicator consists of a quantity whose recording is not mandated by an external organisation. Under-reporting can occur even for those incidence rates describing events that do not have a physical consequence or do not require a course of action.[123] Under-reporting can lead to the veracity of these metrics to be questioned. • Difficult to compare a company performance with the performance of the sector due to the high values used for the normalisation (ie 100,000 employees). • Requires root cause analysis of performance is to be improved.
Use	• Government agencies (eg Health and Safety Executives (HSE) in UK, Occupational Safety and Health Administration (OSHA) in USA[124]). • Examples of contractors, developers and infrastructure operators using incidence rates can be found in the literature (eg Barratt Developments[125], Kier Group[126],Mott Macdonald[127], Network Rail[128], Jacobs[129]).

[120] HSE, 2015. *Injury frequency rates*. Available at: http://www.hse.gov.uk/statistics/adhoc-analysis/injury-frequency-rates.pdf (Accessed: 08/05/2019).

[121] HSE, 2012. *Leadership and worker involvement toolkit. Guidance to accompany the Site Measurement Aid*. Available at: http://www.hse.gov.uk/construction/lwit/assets/downloads/site-measurement-aid-supporting-guidance.pdf (Accessed: 08/05/2019).

[122] Hallowell, M.R., Hinze, J.W., Baud, K.C. and Wehle, A., 2013. Proactive construction safety control: Measuring, monitoring, and responding to safety leading indicators. *Journal of Construction Engineering and Management, 139(10)*, p.04013010.

[123] Jazayeri, E. and Dadi, G.B., 2017. Construction safety management systems and methods of safety performance measurement: A review. *Journal of Safety Engineering, 6(2),* pp.15-28.

[124] https://www.rit.edu/~w-outrea/OSHA/documents/Module5/M5_IncidentRates.pdf (Accessed: 16/05/2019).

[125] https://www.constructionenquirer.com/2018/09/05/barratt-sets-target-to-build-20000-homes-a-year/ (Accessed: 09/05/2019).

[126] https://www.kier.co.uk/media/2643/kier-cr-reporting-guidelines-2018-v3-20181008.pdf (Accessed: 10/05/2019).

[127] Mott MacDonald Group limited, 2018. *Report and financial statements 31 December 2017*.

[128] https://www.networkrail.co.uk/who-we-are/how-we-work/performance/safety-performance/workforce-safety/ (Accessed: 16/05/2019).

E.1.6 Lagging metrics – Severity rate

Severity rate	
Method of measurement	The severity rate is defined as the ratio between the number of lost work days and the number of recordable incidents[130]. It provides information on the average lost work days associated with each event.
Merits	• Relatively easy to calculate. • Objective, reliable, verifiable.
Disadvantages	• Does not relate directly to strategic objectives. • It is a lagging indicator. • It does not provide information on the type of incident that occurred. • It can be misleading because the same rate could result from different number of incidents of different severity. For example, the same severity rate would be obtained considering one incident that led to four lost work days or four incidents that led to one lost work day each.
Use	• Not widely adopted due to its limitations.

[129] Jacobs, 2018. Annual report. Available at: https://www.jacobs.com/sites/default/files/files/2018-12/Jacobs-2018-Annual-Report.pdf (Accessed: 14/05/2019).

[130] Jazayeri, E. and Dadi, G.B., 2017. Construction safety management systems and methods of safety performance measurement: A review. *Journal of Safety Engineering, 6(2),* pp.15-28.

E.2. Labour productivity

E.2.1 Gross value added/number of jobs[131]

Gross value added/number of jobs	
Method of measurement	GVA = Turnover (or sales) less the cost of bought in goods & services (excl. employee costs). So GVA is the value of work completed or invoiced less the cost of materials, subcontractors and other bought-in services. This is most readily measured monthly when interim invoices are submitted. The ONS calculates the number of jobs as the number of people in work taken from the Annual Survey of Hours and Earnings and the Labour Force Survey.
Merits	• This metric is one published by the ONS[132]. It is therefore objective, reliable, consistent and verifiable. • Theoretically, it can be rolled up from project to site to organisation to national level. • It requires the collection of no data that is not already collected and is therefore cost-effective, but requires the cooperation of subcontractors. • Data can be collected historically or currently over any desired period. • It can be used to compare labour productivity on each plot or site. • It reflects the strategic objective.
Disadvantages	• It fails to distinguish between full-time and part-time jobs or between differences in hourly costs eg between skilled and unskilled labour or premium and standard time. • It is difficult to measure the number of jobs associated with a plot or site if the employment is not continuous. • Although it relates to strategic objectives, it provides no diagnostic information about the causes of differences in productivity and therefore does not contribute significantly to effective decisions and process improvements. • There are issues to be resolved about which people should be included in the number of jobs, and how they should be measured (eg head office staff), though these can be overcome. • It needs to be modified in the case of off-site manufacture to take account of investment in manufacturing facilities. • It is an unfamiliar metric which may not be meaningful to users.
Use	• Used extensively by Government and mandated by the EU. • To our knowledge, it has not been used to measure productivity below the national level. • Not used for site or organisation level measurements.

E.2.2 Gross value added/total hours worked[133]

Gross value added/ total hours worked	
Method of measurement	As GVA/number of jobs but using hours instead of jobs. Hours worked should be available from site and subcontractor records.
Merits and disadvantages	• As GVA/number of jobs except that the difficulties of distinguishing between full-time and part-time employees is overcome, and it is easier to measure the number of hours input than the number of jobs.
Use	• Used extensively by Government and mandated by the EU. • To our knowledge, it has not been used to measure productivity below the national level. • Not used for site or organisation level measurements.

131 https://www.ons.gov.uk/economy/economicoutputandproductivity/productivitymeasures (Accessed: 19/06/2019).

132 https://www.ons.gov.uk/economy/grossvalueaddedgva (Accessed: 22/07/19).

133 Ibid.

E.2.3 Gross value added/labour cost

Gross value added/labour cost	
Method of measurement	As GVA/number of jobs but using labour costs rather than number of jobs. Labour costs should be available from site and subcontractor records.
Merits and disadvantages	• As GVA/number of jobs, but overcomes the issues around part-time employees and differences in hourly costs. It is also very meaningful, since it can only be increased either by increasing the Gross Value Added with at the same labour cost, or producing the same GVA for lower labour costs. However, it is not a statistic that has been used previously and may therefore be regarded as experimental, although discussions with statisticians indicate that it is perfectly valid.
Use	• New metric; not used anywhere but finding favour with Ministry for Transport.

E.2.4 Value of work completed/total hours worked

Value of work completed/total hours worked	
Method of measurement	Value may be measured from invoices submitted to the client. It is most frequently calculated by multiplying the quantity of work completed by the predicted or tendered unit price.
Merits and disadvantages	• This metric shares the same merits as GVA/labour total hours worked except that because the data is not collected by the ONS, it is unlikely to be as objective, reliable, consistent and verifiable. However it is a more familiar measure than GVA/total hours worked and may therefore be more meaningful to users.
Use	• Used widely throughout the construction industry.[134]

E.2.5 Value of work completed/labour cost

Value of work completed/labour cost	
Method of measurement	As value of work completed/total hours worked, but using labour costs rather than number of jobs.
Merits and disadvantages	• As value of work completed/total hours worked, but overcomes the issues around part-time employees and differences in hourly costs.
Use	• No reported use in the literature or elsewhere.

[134] Ibid.

E.2.6 Delays

Delays	
Method of measurement	Since delays lasting longer than 15 minutes are known to be the major cause of loss of labour productivity[135], they may be used as a surrogate. Their duration and cause may be recorded by any of the methods previously described: by the operatives themselves, by supervisors, intermittently by visiting data gatherers or by continuous observation. They are measured daily. As an aid to recording, a Delay Management Tool is under development using a personal handheld device and a powerful analytical engine. Collecting data on delays has been relatively widespread in the industry, if for no other reason than settling claims for delay and disruption.
Merits	• Simple, easily understood data with which people are familiar. • Cost effective if collected by the operatives themselves, though expensive if continuous observation is undertaken. • Can be analysed at gang, plot, site or company level. • Provides valuable diagnostic information which can drive effective decisions and process improvements. • Valuable in the quantification of claims for delay and disruption. • An objective, reliable and consistent metric.
Disadvantages	• Does not relate as directly as some other metrics to the consortium's strategic objectives. • Is not a direct measure of productivity, and is best used in conjunction with some other metric such as GVA/cost of labour to demonstrate changes in productivity caused by changes in delay frequency and duration. • Accuracy depends on the capability of the data gatherer and may therefore be difficult to verify.
Use	• Used in an ad hoc fashion by many companies in the form of site diaries. • No report of the use of a structured approach to the measurement of delays other than by researchers using intermittent observations.[136]

[135] H Horner, R.M.W. and Duff, A.R., 2001. *More for Less A Contractor's Guide to Improving Productivity in Construction*. CIRIA, London.

[135] Noor, I. 1992. *A study of the variability of Labour Productivity in Building Trades* (PhD Thesis University of Dundee, UK)

[136] Ibid.

E.2.7 Earned value/Actual cost[137]

Earned value/Actual cost	
Method of measurement	This is a metric used extensively in the petrochemical industry and in the USA, but much less frequently in the UK construction industry. Earned value is the quantity of work of each kind completed multiplied by its unit value which may be taken from a tender, from internal records or from industry "norms". Actual costs are the costs incurred in producing the work completed and may be taken from company cost and financial control systems.
Merits	• It relates directly to the consortium's strategic objectives. • It is a familiar measure. • It is an objective measure, and if valuations are undertaken as a matter of routine, at site level it requires the collection of no extra data and is therefore very cost-effective, reliable, consistent and verifiable.
Disadvantages	• Value includes the value added by materials and subcontractors. Thus differences in the metric may arise from differences in material values or subcontractor prices rather than productivity. • If a level of detail below site level is required at say, task level, it is necessary to allocate the input costs to each individual task. This may be difficult if not impossible. • Comparisons between one site and another may be distorted by the unit values assigned to each quantity of work, for example, if different predictions of value are used. • It provides no diagnostic information about the causes of differences in productivity and therefore does not contribute significantly to effective decisions and process improvements. • It may be necessary to collect data from subcontractors.
Use	• Used extensively in the petrochemical industry, and most notably and successfully in construction of Heathrow terminal 5. • No reported use elsewhere, though known to be piloted by Laing before their demise.

E.2.8 Earned hours/Actual hours

Earned hours/Actual hours	
Method of measurement	Earned hours are calculated by multiplying the quantity of work completed by so-called norms, which are standard quantities of work per person hour derived from detailed time and motion studies.
Merits	• It relates to the consortium's strategic objectives. • At a site level, if valuations and therefore quantities are measured as a matter of routine, it is very cost-effective and allows productivity in different activities to be combined. • It focusses absolutely on labour undistorted by the cost of materials or subcontract prices. • Provided robust norms are available, the metric is objective, reliable. consistent and verifiable.
Disadvantages	• No widely accepted norms exist in the construction industry. • It is not a familiar metric. • If a level of detail below site level is required at say, task level, it is necessary to allocate the input costs to each individual task. This may be difficult if not impossible. • It provides no diagnostic information about the causes of differences in productivity and therefore does not contribute significantly to effective decisions and process improvements. • It may be necessary to collect data from subcontractors.
Use	• This is another metric used extensively in the petrochemical industry but which has so far penetrated the construction industry in only a very small number of projects.

[137] Oglesby, C.H., Parker, H.W. and Howell, G.A., 1989, *Productivity Improvement in Construction*, McGraw-Hill, New York.

E.2.9 Construction Industry Institute (CII) Construction Performance Assessment (CPA)

CII Performance Assessment (CII CPA)	
Method of measurement	Formerly known as the CII Benchmarking and Metrics, this approach, developed in the 1980s[138],[139] uses an earned value type approach to express quantity of output in one type of activity in an equivalent quantity of output in a different activity[140].
Merits	• obviates the need to allocate labour resources to individual activities. • Simple. unambiguous and easy to understand.
Disadvantages	• Requires the determination of "standard outputs" in each activity. • The extent of the activities for which standards have been developed is limited, and it is not clear to what extent the necessary baseline data has been collected.
Use	• There are indications that this method of measurement has found no traction in the American contracting community[141].

[138] Thomas, H.R and Mathews, C.T. 1985 *Methods of productivity measurement*. Report to the Construction Industry institute, Austin, Texas.

[139] Thomas H.R, Sanders, S.R., Horner R.M.W., 1989 *Procedures Manual for collecting productivity and related data of labour-intensive activities on commercial construction projects*. Final report to the National Science Foundation of America, Grant No MSM-8611600. The Pennsylvania Transportation Institute, Pennsylvania State University, PA, USA.

[140] Park, H.S., Thomas, S.R. and Tucker, R.L., 2005. Benchmarking of construction productivity. *Journal of construction engineering and management, 131(7*), pp.772-778.

[141] https://www.construction-institute.org/resources/knowledgebase/best-practices/benchmarking-metrics/topics/bm-vbp (Accessed: 19/06/2019).

E.2.10 Productivity index

Productivity index	
Method of measurement	In the technique known as activity sampling[142], the productivity index is defined as the ratio of the number of operatives observed to be doing value adding activities to the total number observed. Activity sampling is a technique widely used in the USA in the 1950's, but rarely used nowadays in construction. At its simplest, a trained observer walks round a site at random intervals recording on a counter whether each operative is working or idle. When sufficient data has been collected to be statistically robust, "productivity" is calculated as the ratio of the number of observations made of people working to the total number of observations. In more sophisticated approaches observations are categorized into a number of activities such as "transporting materials", "waiting", and "meeting".
Merits	• Objective, reliable verifiable, and consistent. • Can shed light on where waste is occurring and can therefore drive decision and process improvements. • Simple. unambiguous and easy to understand.
Disadvantages	• Does not measure productivity as defined in the Glossary of Terms in Appendix C. It measures inputs, but not outputs. There is doubt as to whether a correlation exists between productive time and productivity.[143,144] • Can be expensive if used extensively. • Does not distinguish between short and long periods of idleness. Research show that interruptions lasting less than 15 minutes have no impact on output[145]. Short breaks are needed to alleviate muscle fatigue.
Use	• Numerous reports of use in the 1960s, 70s, and 80s, but doubts cast on its validity. • Re-incarnated by BRE in their product "Calibre" which has been used on numerous occasions but which has not enjoyed extensive uptake.

[142] Thomas, H.R. and Daily, J., 1983. Crew performance measurement via activity sampling. *Journal of Construction Engineering and Management, 109(3)*, pp.309-320.

[143] Thomas, H.R., Holland, M.P. and Gustenhoven, C.T., 1982. Games people play with work sampling. Journal of the Construction Division, 108(1), pp.13-22.

[144] Peer, S. 1986. *An Improved Systematic Activity Sampling Technique for Work Study.* Construction Management and Economics, Vol 4.

[145] Noor, I. 1992. *A study of the variability of Labour Productivity in Building Trades.* PhD Thesis University of Dundee, UK.

E.3. Quality

E.3.1 Field Rework Index (FRI)

<table>
<tr><th colspan="2">Field Rework Index (FRI)</th></tr>
<tr><td>Method of measurement</td><td>Provides qualitative information on the likelihood that costs will arise due to rework. It can be determined by totalling the scores (from 1 to 5) given to 14 questions. Details of the questions can be found in ref 146. Percentages of expected rework costs for score bands are summarised in the table below. It should be noted that the suggested percentages reflected the US construction sector performance since about the year 2000.
<table><tr><th>FRI score</th><th>Typical percentage of rework</th></tr><tr><td>14 – 29</td><td>2.5%</td></tr><tr><td>30 – 44</td><td>5.0%</td></tr><tr><td>45 – 70</td><td>7.0%</td></tr></table></td></tr>
<tr><td>Merits</td><td>• If correctly applied, it allows the prediction of future costs due to quality issues.</td></tr>
<tr><td>Disadvantages</td><td>• Typical percentage values of rework refer to the US construction industry. Care must be taken when applying this method elsewhere.
• Future costs are estimated on the basis of qualitative – and hence non-objective – information.</td></tr>
<tr><td>Use</td><td>• Developed by the US based Construction Industry Institute (CII) in the early 2000 [147 in 148]. No example of companies adopting it was found.</td></tr>
</table>

E.3.2 ISO 9001 Accreditation

<table>
<tr><th colspan="2">ISO 9001 Accreditation</th></tr>
<tr><td>Method of measurement</td><td>Defined as the percentage of companies within the construction sector with an ISO 9001 accreditation. This metric, the use of which has been suggested by CLC[149], aims to describe the quality performance of the whole industry.</td></tr>
<tr><td>Merits</td><td>• Obtaining an ISO 9001 certification forces a company to think about its quality management system and can induce a cultural change in it.</td></tr>
<tr><td>Disadvantages</td><td>• The amount of effort in terms of time and cost required to correctly implement and maintain a certified quality management system is not insignificant.
• Provides little evidence of causes of poor quality other than through non-compliances.
• This metric can be used only to compare the performance of one industry with another.</td></tr>
<tr><td>Use</td><td>• ISO 9001 accreditations are adopted in most sectors. According to ISO[150], over 37,450 certificates were valid in the UK in 2017. Information on the number of ISO 9001 certificates released to companies belonging to the construction industry was not found.</td></tr>
</table>

[146] web.engr.oregonstate.edu/~rogged/frifinal51.doc (Accessed: 28/05/2019).

[147] Rogge, D.F., Cogliser, C., Alaman, H. and McCormack, S., 2001. An investigation of field rework in industrial construction. *Construction Industry Institute*, pp.153-186.

[148] CITB, 2016. *Get it Right Initiative. Literature Review*. Available at: https://getitright.uk.com/reports/ (Accessed: 27/05/2019).

[149] CLC, 2018. *Innovation in building workstream. Housing industry metrics.* Available at: http://www.constructionleadershipcouncil.co.uk/building-metrics/ (Accessed: 27/05/2019).

[150] https://isotc.iso.org/livelink/livelink?func=ll&objId=18808772&objAction=browse&viewType=1 (Accessed: 30/05/2019).

E.3.3 Yield

Yield	
Method of measurement	Defined as the ratio between the number of non-defective items and the total number of items manufactured. It is one of the basic quality measures adopted in manufacturing[151]. Sometimes it is expressed as a percentage. Variants of this metric are: • First Time Yield (FTY) which is the ratio of the total number of items that were found to be defect-free after the first inspection to the total number of items manufactured. • Rolled Throughput Yield (RTY) defined as the product of the FTY of all the processes involved in manufacturing an item.
Merits	• Objective, reliable, verifiable, mature. • Allows the identification of issues and sudden non-conformances within a production process.
Disadvantage	• Does not provide information on the type of issues encountered. • Can be applied only to cases in which the output of the manufacturing (construction) process is always the same and can be considered a single item. • Can be applied only when the manufacturing (construction) process adopted is exactly the same for each of the resulting items. • Does not relate to strategic objectives
Use	• Manufacturing industry. No examples within the construction sector. • Could be adopted for measuring the quality of off-site manufacturing output if 'items' or 'components', are properly identified and manufactured in a controlled environment.

E.3.4 Costs due to error/total construction cost

Costs due to error/total construction cost	
Method of measurement	This metric describes the contribution of costs due to errors in process and product, whether or not they result in rework as a percentage of the total project value. Costs may be limited to the direct costs incurred by the (sub)contractor while rectifying the errors and defects, or may include indirect costs too[152].
Merits	• Simple, verifiable, objective, reliable. • Relates to strategic objectives. • It is a metric based on quantitative data. • More comprehensive than the metric in Section 3.3.3 because it includes both pre and post-occupancy costs. • Allows the performance of a project to be tracked while still ongoing (ie during the construction phase).
Disadvantage	• May require special measures to collect the necessary data. • Focusses on the effects (ie the increase in cost) rather than on the causes that lead to the need for rework/rectification. • Describes the lack of quality rather than how good the product is.
Use	• One of the most widely used metrics that can be found in the literature (see the Get It Right Initiative literature review report for a comprehensive list of authors citing this metric[153]).

[151] Lu, Y., Morris, K.C. and Frechette, S., 2016. Current standards landscape for smart manufacturing systems. National Institute of Standards and Technology, NISTIR, 8107, p.39.

[152] CITB, 2015. *Get it right. A strategy for change.* Available at: https://getitright.uk.com/reports/ (Accessed: 27/05/2019).

[153] CITB, 2016. *Get it Right Initiative. Literature Review.* Available at: https://getitright.uk.com/reports/ (Accessed: 27/05/2019).

E.3.5

E.3.5 Number and type of items that did not pass visual inspection

Number and type of items that did not pass visual inspection	
Method of measurement	This metric is defined as the number of items of each type that failed a visual quality inspection (ie a snagging inspection) and that, hence, required rectification work. Can be measured only if a visual inspection plan containing all the items that have to be inspected is available. Based on the form used for collecting data, information extracted from a visual inspection plan could be used for determining additional indicators. For example: percentage of items that failed the visual inspection, how many times a given issue has been recorded, the percentage of items rectified between one inspection and another, how many items did not pass a visual inspection for the same reason (eg due to poor design information).
Merits	• Depending on the type and the granularity of the collected data it can be very detailed and provide an accurate picture of the quality of the construction works. • It forces the company to identify the items that might present issues and that should hence be inspected. • If consistently and constantly adopted, it can induce a behavioural change in the workforce because it provides timely information on the types of issues and the corrective actions to adopt. • Allows the performance of a project to be tracked while still ongoing (ie during the construction phase). • Identifies specific areas of weakness.
Disadvantages	• Costs associated with data collection (ie site observer) and data handling (eg person digitalising and analysing data manually or cost of automation if the process is automated. • Subjected to site observer/auditor bias and experience. • Not coupled to cost information.
Use	• Examples can be found in M&E companies (eg NG Bailey[156]).

[156] Bailey, N. G., 2018. A best practice approach to quality in MEP services. *Quality in construction summit,* 27 November 2018, Manchester, UK. Available at: https://summits.ukconstructionweek.com/qic/quality-in-construction-summit-2018#presentations (Accessed: 28/05/2019).

E.4. Cost

E.4.1 Average construction cost/m² (GIFA)

Average construction cost/m² (GIFA)	
Method of measurement	The average construction cost per m² is calculated by dividing the total construction cost of a house or group of houses by the Gross Internal Floor Area (GIFA) [157].
Merits	• Relates to strategic objectives, relatively easy to determine, simple, objective, widely understood, reliable and verifiable. • One of the principal determinants of profitability.
Disadvantages	• Takes no account of differences in quality or layout. • Requires accurate monitoring of costs of all resources used in construction. • Preliminaries may not be accounted for consistently.
Use	• Widely adopted in different sectors of the construction industry.[158] • One of the metrics suggested in the International Construction Measurement Standards[157], CLC (2018)[159] and RCIS.[160]

E.4.2 Construction cost/bedroom

Construction cost/bedroom	
Method of measurement	This metric is the total construction cost divided by the number of bedrooms.
Merits and disadvantages	• As for construction cost/m².
Use	• Widely adopted in different sectors of the construction industry (eg hotels, hostels, student accommodations).[161, 162]

[157] See-Lian, O., Muse, A., O'Sullivan, G., Aronsohn, A., Baharuddin, D., Chatzisymeon, T., Damot, W., Fadason, R., Flanagan, R., Gardin, M. and Horner, M., 2017. *International Construction Measurement Standards: Global Consistency in Presenting Construction Costs.*

[158] BCIS, 2018. *Comprehensive building price book – minor works. 35th edition 2018.*

[159] CLC, 2018. *Innovation in building workstream. Housing industry metrics.* Available at: http://www.constructionleadershipcouncil.co.uk/building-metrics/ (Accessed: 27/05/2019).

[160] RICS, 2012. *NMR1 New rules of measurement. Order of cost estimating and cost planning for capital building works.*

[161] Higham, A., Bridge, C. and Farrell, P., 2016. *Project finance for construction.* Routledge.

[162] RICS, 2012. *NMR1 New rules of measurement. Order of cost estimating and cost planning for capital building works.*

E.4.3 Cost variance

Cost variance	
Method of measurement	Cost variance is defined as the difference between the actual cost and the budgeted cost of work performed[163]. It may be calculated at the organisation, site, plot, element or item level. It is closely related to the Cost Performance Indicator (CPI) which is defined as the ratio of the budgeted cost of work performed to the actual cost.
Merits	• Allows cost performance in different activities to be aggregated. • Allows cost comparisons to be made in a consistent way. • Depending on the level of granularity, may not require a detailed cost breakdown. • Provides an indication of profitability. • Over time, allows the development of "norms" or average levels of performance for relevant activities. • Oscillations in a project CPI value can be an indicator of poor management capabilities of the appointed contractor.[164]
Disadvantages	• Not directly related to strategic objectives. • Costs must be monitored at the same level of detail as value. • Depending on the level of granularity, this may require very detailed cost monitoring. • Assumes that value is calculated accurately and consistently.
Use	• Widely used in the petrochemical industry but limited use in the construction.[165]

[163] Orgut, R.E., Zhu, J., Batouli, M., Mostafavi, A. and Jaselskis, E.J., 2015, June. A review of the current knowledge and practice related to project progress and performance assessment. In *5th International/11th Canadian Society for Civil Engineering Construction Specialty Conference*, Vancouver, Canada.

[164] Wauters, M. and Vanhoucke, M., 2014. Study of the stability of earned value management forecasting. *Journal of Construction Engineering and Management*, *141*(4), p.04014086.

[165] Netto, J.T., Quelhas, O., França, S., Meiriño, M. and Lameira, V., 2015. Performance Monitoring Using EVM Indicator: a study case of construction projects in the public sector in Brazil. *Sistemas & Gestão*, *10*(1), pp.194-202.

E.4.4 Change in cost of construction

Change in cost of construction	
Method of measurement	The use of this metric was suggested by the KPI Woking Group in 2000[166]. It is defined as the 'Change in the current normalised construction cost of a project at Commit to Construct point [...] compared with one year earlier, expressed as a percentage of the one year earlier cost'. It is expressed in percentage and it can be calculated using the following formula: $$Cost\ of\ construction = \frac{(A - B - C - D) - E}{E} \times 100$$ where: *A* = Rate per m² from tendered cost for construction at the moment a contractor/constructor signs the contract; B = 'Higher quality than year earlier project (assessed)' C = 'More expensive region than year earlier project (assessed)' D = 'Resource costs have increased since year earlier project (published)' *E* = Rate per m² from tendered cost for construction at the moment a contractor/constructor signs the contract *'for the year earlier project'*.
Merits	• Takes account of quality, temporal and locational differences between one house and another. • Measures changes in gross efficiency over time.
Disadvantages	• Not directly related to strategic objectives. • Data may not be readily available. • Elements of subjectivity.
Use	• Recommended by the KPI Working Group[166], but no evidence of widespread uptake.

E.4.5 Prelims cost/capital cost

Prelims cost/capital cost	
Method of measurement	This is the ratio of the cost of prelims to the capital construction cost.
Merits	• Relatively simple to determine. • Popular with Government.
Disadvantages	• Does not relate to strategic objectives. • Requires accurate monitoring of costs. • If used at the plot level, requires the consistent and accurate allocation of prelim costs to each plot. • Implies that a reduction in preliminaries is desirable. This may not necessarily be the case eg ignores the savings to be made by increasing the amount of craneage or site supervision.
Use	• The use of this metric has been suggested by CLC (2018a)[167] although it is confusingly given the title of '*Prelims cost per home built*'. • No data or benchmarking figures are available. CLC suggested that benchmarking data could be collected by circulating annual surveys among CLC members.[167]

[166] KPI Working Group, 2000. *KPI Report for the Minister for Construction.* Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/16323/file16441.pdf (Accessed: 04/06/2019).

[167] CLC, 2018. *Innovation in building workstream. Housing industry metrics*. Available at: http://www.constructionleadershipcouncil.co.uk/building-metrics/ (Accessed: 27/05/2019).

E.4.6 Cost growth (%)

Cost growth (%)	
Method of measurement	This is a relative performance indicator that compares the actual and forecast construction costs. It is expressed as a percentage of the forecasted construction cost and is obtained from the following formula: $$Cost\ growth = \frac{Actual\ construction\ cost - Construction\ cost\ value\ in\ the\ contract}{Construction\ cost\ value\ in\ the\ contract} \times 100$$ '*Cost overrun*' is often used as synonym for '*Cost growth*'[168].
Merits	• Simple to determine. • Can be applied at different levels (eg project level, phase level, activity level) depending on the available data. • Can provide up to date information on the expenditure and profitability associated with a project. • In sectors like Oil & Gas it is adopted as an indicator of project cost predictability too.[169]
Disadvantages	• Not directly related to strategic objectives. • Used as a stand-alone metric it does not allow the determination of the reasons underlying the overrun.
Use	• Widely adopted by the construction industry.

E.4.7 Phase cost ratio

Phase cost ratio	
Method of measurement	This is the ratio of the cost of a given phase of construction to the total cost of the project[170].
Merits	• Relatively simple to determine. • For housing projects, very similar to cost per item or element.
Disadvantages	• Not directly related to strategic objectives. • Requires accurate allocation of costs of all resources used in construction. • Preliminaries may not be accounted for consistently.
Use	• Only one reference about its use has been found, and it is related to the Oil & Gas industry.[170]

[168] Asiedu, R.O., Frempong, N.K. and Alfen, H.W., 2017. Predicting likelihood of cost overrun in educational projects. *Engineering, Construction and Architectural Management*, *24*(1), pp.21-39.

[169] Rui, Z., Li, C., Peng, F., Ling, K., Chen, G., Zhou, X. and Chang, H., 2017. Development of industry performance metrics for offshore oil and gas project. *Journal of Natural Gas Science and Engineering*, *39*, pp.44-53.

[170] Rui, Z., Li, C., Peng, F., Ling, K., Chen, G., Zhou, X. and Chang, H., 2017. Development of industry performance metrics for offshore oil and gas project. *Journal of Natural Gas Science and Engineering*, *39*, pp.44-53.

E.4.8 citiBLOC/m²

citiBLOC/m²	
Method of measurement	This is defined as the number of citiBLOCs required to build a square metre of an asset[171]. A citiBLOC is defined as the average price of a basket of the '*representative construction items including materials (various quantities of concrete, steel, glass, plasterboard and softwood studs); labour (electricians, carpenters, painters and unskilled labour at various total hours and charge out rates); and plant (mobile crane)*'[171]. The correlation between citiBLOCs of two different countries has been found to be similar to that of their Big Mac Index[172]. The Big Max Index is a Purchasing Power Parities index published by *The Economist* since 1986[173] which is widely used by economists.
Merits	• Not related to strategic objectives. • Allows benchmarking and comparison across countries.
Disadvantages	• Complex. • Different construction methods might require different citiBLOC baskets.
Use	• No practical examples of companies adopting this metric were found. All references found in the literature refer to the work published by Langston and its group. • Its use along with qualitative analysis of the causes underlying cost differences has been considered 'highly prospective' by the Australian Government[174].

[171] Langston, C., 2015. Performance measures for construction. In *Measuring Construction* (pp. 173-198). Routledge.

[172] Bröchner, J., 2015. Measuring Construction: Prices, Output and Productivity. *Construction Economics and Building*, *15*(3), pp.98-99.

[173] The Economist, 2016. *The Big Mac Index*. Available at: https://www.economist.com/news/2019/01/10/the-big-mac-index (Accessed: 12/06/2019).

[174] Australian Government, 2014. *Public Infrastructure. Productivity Commission Inquiry report. Volume 2*. Available at: https://www.pc.gov.au/inquiries/completed/infrastructure/report (Accessed: 12/06/2019).

E.5. Time

E.5.1 Overall time (or Programme duration)

Overall time (or Programme duration)	
Method of measurement	This metric is defined as the elapsed time required to complete a project. It is calculated by subtracting the starting date from the completion date.[175] It can be determined by applying the so called '*Incremental milestone method*', which is based on determining the duration of activities between pre-set milestones[176]. By applying the same principle to specific activities of project phases (ie making the difference between ending and starting dates) it is possible to determine a variety of indicators such as, for example, the overall time spent in rectifying issues, the overall time spent waiting for deliveries, etc. It has been suggested that this metric is the most appropriate for measuring "time" in those activities which do not have easily definable milestones (eg cleaning)[176]. If calculated during the pre-construction phase of a project, this metric can be used to define the scheduled delivery programme of a project[177]. It can be expressed in days, weeks, months or years.
Merits	• Relates to strategic objective. • Objective, verifiable, easy to determine, to communicate, and to understand. • Can be used for determining additional time-related metrics.
Disadvantages	• A lagging indicator. It does not allow the extraction of information if the pre-set milestone (eg the end of the project) has not been reached. • Is not normalised, so inter-project comparisons are difficult. • In any case, provides no information about the causes of any variances unless phases are quite short.
Use	Used worldwide in the construction industry (eg in USA[176]).

E.5.2 Time/m^2

Time/m^2	
Method of measurement	This metric is defined as the average time required to produce a unit of output, where the output is here expressed as a unit of area, usually the gross internal floor area. It is a particular case of the metrics introduced in Section 3.5.2 where the output unit is expressed in m^2. Time is measured as described in Section 3.5.2. Unit area is usually taken as GIFA measured form the construction drawings. For housing, CLC (2018a)[178] suggests using '*Time on site*' for determining it and to express it as days/m^2. CLC (2018b)[179] call it '*Speed'* and expresses it as man-hrs/m^2 which is effectively a measure of productivity rather than time.
Merits and disadvantages	• As Section 3.5.2.
Use	• Examples can be found in the literature (eg housing[179]).

[175] Sanchez, A. and Joske, W., 2016. Metrics dictionary. In *Delivering Value with BIM: A Whole-of-Life Approach* (pp. 297-336).

[176] Orgut, R.E., Zhu, J., Batouli, M., Mostafavi, A. and Jaselskis, E.J., 2015, June. A review of the current knowledge and practice related to project progress and performance assessment. In *5th International/11th Canadian Society for Civil Engineering Construction Specialty Conference, Vancouver, Canada*.

[177] www.laingorourke.com/~/media/lor/files/annual-review-2014/performance.pdf (Accessed: 06/06/2019).

[178] CLC, 2018. *Innovation in building workstream. Housing industry metrics.* Available at: http://www.constructionleadershipcouncil.co.uk/building-metrics/ (Accessed: 27/05/2019).

[179] CLC, 2018b. *AIMC4 Casestudy.* Available at: http://www.constructionleadershipcouncil.co.uk/wp-content/uploads/2018/10/181022-CLC-Casestudy-AIMC4.pdf. (Accessed: 25/02/2019).

E.5.3 Delivery speed

Delivery speed	
Method of measurement	This metric is the inverse of the one cited in Section E.5.2 (ie time/m^2). In Carpenter et al. (2016)[180] this metric is defined as '*Construction intensity*'.
Merits	• As Section 3.5.2.
Disadvantages	• As Section 3.5.2.
Use	• Cited in Sanchez et al. (2016).[181]. • It is cited as one of the metrics for Integrated Project Delivery (IPD) by Hanna (2016)[182]. It is used by some construction companies in USA.

E.5.4 Change in time for construction

Change in time for construction	
Method of measurement	The use of this metric has been suggested by the KPI Woking Group in 2000[183]. It is defined as the 'Change in the current normalised construction time of a project at Commit to Construct point […] compared with one year earlier, expressed as a percentage of the one year earlier time'. It is expressed as a percentage and can be calculated from the following formula: $$Time\ for\ construction = \frac{(A - B + C) - D}{D} \times 100$$ where: *A* = duration of the construction contract period at the moment a contractor/constructor signs the contract; B = 'Higher specification than year earlier project (assessed)' C = 'Smaller than year earlier project (assessed)' *D* = duration of the construction contract period at the moment a contractor/constructor signs the contract '*for the year earlier project*'.
Merits	• Takes account of quality, temporal and locational differences between one house and another. • Measures changes in gross efficiency over time.
Disadvantages	• Not directly related to strategic objectives. • Data may not be readily available. • Elements of subjectivity.
Use	• Suggested by the KPI Working Group[184].

[180] Carpenter, N. and Bausman, D.C., 2016. Project delivery method performance for public school construction: Design-bid-build versus CM at risk. *Journal of Construction Engineering and Management*, *142*(10), p.05016009.

[181] Sanchez, A. and Joske, W., 2016. Metrics dictionary. In Delivering Value with BIM: A Whole-of-Life Approach (pp. 297-336).

[182] Hanna, A.S., 2016. Benchmark performance metrics for integrated project delivery. *Journal of Construction Engineering and Management, 142*(9), p.04016040.

[183] KPI Working Group, 2000. *KPI Report for the Minister for Construction*. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/16323/file16441.pdf (Accessed: 04/06/2019).

[184] KPI Working Group, 2000. *KPI Report for the Minister for Construction*. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/16323/file16441.pdf (Accessed: 04/06/2019).

E.5.5 Project schedule variation (%)

Project schedule variation (%)	
Method of measurement	This metric, expressed as a percentage, describes the variation to a project's schedule. It is defined by the following equation[185]: $$Schedule\ variation = \frac{Planned\ schedule - Actual\ schedule}{Plannned\ schedule} \times 100$$ Data is taken from the planned programme and from a record of the actual start and finish times of site activities
Merits	• Easy to determine. According to de Carvalho et al. (2015)[185], data for its measurement can be extracted from '*Project status reports'*. • Provides information on schedule compliance.
Disadvantages	• Does not relate directly to strategic objectives. • Does not allow the identification of possible causes of delays. • Not normalised to take account of different project characteristics.
Use	• Used by a variety of South American industries (eg energy, oil and gas, maintenance, IT, manufacturing).[185]

E.5.6 Schedule growth (%)

Schedule growth (%)	
Method of measurement	This metric, expressed as a percentage, is the opposite of metric in Section E.5.5. It helps comparing planned with actual durations. It is defined as: $$Schedule\ growth = \frac{Actual\ schedule\ -\ Planned\ scheduled}{Plannned\ schedule} \times 100$$ Data is taken from the planned programme and from a record of the actual start and finish times of site activities. It can be applied at project level or at phase level[186,187,191] and, depending on who is the stakeholder measuring it, it might have different boundaries (eg an owner will be interested in the duration between the beginning and the end of the handover procedure; a contractor might be interested in the construction phase only)[188]. Cases in which the *Planned schedule* is replaced by the *Contracted Delivery Time* can be found in the literature[189].
Merits	• As Section E.5.5.
Disadvantages	• As Section E.5.5.
Use	• Adopted by North American construction companies involved in building projects.[190,191] • It is one of the metrics adopted by researches for investigating the performance of different project delivery methods (eg Design and Build vs Construction Management at Risk).[192,193]

[185] de Carvalho, M.M., Patah, L.A. and de Souza Bido, D., 2015. Project management and its effects on project success: Cross-country and cross-industry comparisons. *International Journal of Project Management*, *33*(7), pp.1509-1522.

[186] Orgut, R.E., Batouli, M., Zhu, J., Mostafavi, A. and Jaselskis, E.J., 2016. Metrics that matter: Evaluation of metrics and indicators for project progress measurement, performance assessment, and performance forecasting during construction. In *Proc., Construction Research Congress*.

[187] Carpenter, N. and Bausman, D.C., 2016. Project delivery method performance for public school construction: Design-bid-build versus CM at risk. *Journal of Construction Engineering and Management*, *142*(10), p.05016009.

[188] Kim, S.B., 2014. Impacts of knowledge management on the organizational success. *KSCE Journal of Civil Engineering*, *18*(6), pp.1609-1617.

[189] Ramsey, D., El Asmar, M. and Gibson Jr, G.E., 2015. Benchmarking the Procurement Performance of Single-Step Design-Build. *Working Paper Proceedings, Engineering Project Organization Conference*, 24-25 June 2015, Edinburgh, UK.

E.5.7 Project schedule factor

Project schedule factor	
Method of measurement	This metric can be obtained by applying the following equation[194]: $$Project\ schedule\ factor = \frac{Actual\ total\ project\ duration}{Initial\ predicted\ project\ duration + Duration\ of\ approved\ changes}$$
Merits	• Provides information on the effect of changes on the programme and of changes that have not been approved. • Otherwise, as Section E5.5.
Disadvantages	• As section E5.5.
Use	• It is one of the project performance metrics suggested by the Construction Industry Institute (CII) in USA.[194]

[190] Franz, B., Esmaeili, B., Leicht, R., Molenaar, K. and Messner, J., 2014, January. Exploring the role of the team environment in building project performance. In *Construction Research Congress 2014* (pp. 1997-2010).

[191] Yun, S., Choi, J., de Oliveira, D.P. and Mulva, S.P., 2016. Development of performance metrics for phase-based capital project benchmarking. *International Journal of Project Management*, *34*(3), pp.389-402.

[192] Sullivan, J., Asmar, M.E., Chalhoub, J. and Obeid, H., 2017. Two decades of performance comparisons for design-build, construction manager at risk, and design-bid-build: Quantitative analysis of the state of knowledge on project cost, schedule, and quality. *Journal of Construction Engineering and Management*, *143*(6), p.04017009.

[193] Ma, M., Fernández-Solís, J.L. and Du, J., 2017. *Does Design-Build (DB) Outperform Construction Management at Risk (CMAR)? A cost and schedule comparative study of DB projects and CMAR projects*. Available at: https://core.ac.uk/download/pdf/154407933.pdf (Accessed: 04/06/2019).

[194] Zhang, D., Nasir, H. and Haas, C.T., 2017. Development of an internal benchmarking and metrics model for industrial construction enterprises for productivity improvement. *Canadian Journal of Civil Engineering*, *44*(7), pp.518-529.

E.6. Predictability

E.6.1 Time predictability – change in completion date

Time Predictability – change in completion date	
Method of measurement	For the partners in the AIMCH project, time predictability is the difference between the actual completion date of a house or part of a house and the date on which completion was first anticipated. It requires a record only of the planned and actual completion dates, and may be measured as the number of houses or parts of houses completed on programme as a percentage of the total number of houses complete.
Merits	• Simple, reflects strategic objectives, understandable, objective, cost effective and verifiable. • Can be rolled up from plot to site to organisation to national level.
Disadvantages	• Provides no information on the causes or severity of overruns so cannot contribute to improvement strategies. • Is not a national indicator so cannot be benchmarked.
Use	• Barratt and many others.

E.6.2 Cost and time predictability – SmartSite KPIs[195]

Cost and time predictability – SmartSite KPIs	
Method of measurement	SmartSite KPIs is an online tool recently developed by Constructing Excellence and BRE. The tool allows organisations to measure and compare the performance of their projects against the rest of the construction industry using the established and nationally recognised Constructing Excellence Construction Industry KPIs. It is necessary to measure times and costs in accordance with the definitions provided in Sections 3.4 and 3.5
Merits & disadvantages	• Generally as Sections 3.6.2 and 3.6.3, but providing the opportunity for benchmarking at the expense of collecting data that does not at this stage completely reflect the AIMCH partners' principal objectives.
Use	• No data available yet.

195 http://constructingexcellence.org.uk/smartsite-kpis-a-new-performance-management-and-productivity-tool-from-constructing-excellence-and-bre/ (Accessed: 17/06/2019).

E.6.3 Safety, productivity, quality and material waste predictability

Safety, productivity, quality and material waste predictability	
Method of measurement	Variability in these metrics will be reflected in the predictability of cost and time. It can be measured using any of the metrics set out in Sections 3.1, 3.2, 3.3, and 3.8 respectively. Predictability in each metric can be determined from the difference between its actual and estimated value. If desired, and for consistency, it can be expressed as a percentage of the estimated value. Thus, $$Predictability\ of\ each\ metric = \frac{actual\ value - estimated\ value}{estimated\ value} \times 100$$ Thus the methods of measurement will be the same as those set out in Sections 3.1, 3.2, 3.3, and 3.8 respectively.
Merits	• Generally as Sections 3.1, 3.2, 3.3, and 3.8 respectively.
Disadvantages	• Generally as Sections 3.1, 3.2, 3.3, and 3.8 respectively, with the following additions. • Requires the derivation of an estimated value for each metric used. • Contributes little additional information relative to the principal objectives, but may add significantly to the cost.
Use	• No reported uses in the literature.

E.7. Material waste

E.7.1 Volume of waste/100 m^2

Volume of waste/100 m^2	
Method of measurement	This metric is determined by dividing the total volume of waste in m^3 produced during the on-site phase of a construction project by the total gross floor area of the resulting building multiplied by 100. It is one of the metrics suggested by SMARTWaste (BRE)[196]. A very similar metric can be obtained by expressing the Volume of waste per m^2 rather than per 100 m^2. Different methods of measurement can be used: • Indirect methods: ◦ By extracting data from the waste management plan after works completion at selected milestones. ◦ By subtracting the quantity of material of each type required according to the project design from the quantity of material of each type delivered to site. • Direct methods: ◦ By means of a dedicated observer who assesses the volume of waste produced while building a given gross floor area.
Merits	• Reflects strategic objectives. • Easy to understand, cost effective, reliable and verifiable. • Simple to determine and applicable to a variety of situations from new build to refurbishment, for which benchmarking values exist.[197,198] • Can be applied at different scales from a specific site, up to a company level. • Potentially, can be determined for different type of wastes: waste from construction materials, waste from packaging materials, waste due to unfit-for-purpose components, waste resulting from excavated materials not utilised for backfilling.[199]
Disadvantages	• If not used along with additional information (eg type of material), it makes it difficult to identify areas were improvement can be effected. • May not allow the determination of the actual volume of waste and the space occupied by voids. • If a waste management plan is used as the only source of data, the resulting indicator might not reflect the current performance of a project.
Use	• According to BRE[201], more than 10,000 companies are using SMARTWaste. It can be assumed that even more companies are using this indicator. Examples of companies using SMARTWaste include Canary Wharf Contractors Limited.[203]

[196] BRE, 2012. Waste Benchmark Data. Available at: http://www.smartwaste.co.uk/filelibrary/benchmarks%20data/Waste_Benchmarks_for_new_build_projects_by_project_type_31_May_2012.pdf (Accessed: 20/05/2019).

[197] Construction Resources & Waste Platform (CRWP), *How benchmark data can be used by contractors*. Available at: http://www.wrap.org.uk/sites/files/wrap/CRWPLeafletContractors.pdf (Accessed: 21/05/2019).

[198] BRE, 2009. *Benchmarks for Predicting and Forecasting Construction Waste - Annex 3*. Available at: randd.defra.gov.uk/Document.aspx?Document=WR0111_9108_FRA.pdf (Accessed: 21/05/2019).

[199] Li, Y., Zhang, X., Ding, G. and Feng, Z., 2016. Developing a quantitative construction waste estimation model for building construction projects. *Resources, Conservation and Recycling*, *106*, pp.9-20.

[201] BRE, https://www.bresmartsite.com/blog/it-all-starts-here-smartwaste-version-2-release/ (Accessed:20/05/2019).

[203] BRE, https://www.bresmartsite.com/blog/credible-data-driving-environmental-performance-improvements-2/ (Accessed:20/05/2019).

E.7.2 Weight of waste/100 m^2

Weight of waste/100 m^2	

Method of measurement	This metric is determined dividing the weight of waste in tonnes produced during the on-site phase of a construction project by the total gross floor area of the resulting building multiplied by 100. It is one of the metrics suggested by SMARTWaste (BRE)[204]. A very similar metric can be obtained by expressing the Weight of waste per m^2 rather than per 100 m^2.
	Different methods of measurement can be used:
	• Indirect methods:
	  ◦ As in Section E.7.1.
	• Direct methods
	  ◦ By means of a dedicated observer who assesses the weight of waste produced while building a given gross floor area. Whenever an exact quantification of the weight of waste is not viable, the observer will have to adopt approximating techniques to infer it based on the 'form of physical layout' and an assumed density of the material.[205,206]

Merits	• Reflects strategic objectives. • Easy to understand, cost effective, reliable and verifiable. • Simple to determine and applicable to a variety of situations spanning from new build to refurbishment, for which benchmarking values exist.[207] • Can be applied at different scales from a specific site, up to a company level. • Potentially, can be determined for different type of wastes: waste from construction materials, waste from packaging materials, waste due to unfit-for-purpose components, waste resulting from excavated materials not utilised for backfilling.[208] • If weight is properly measured, this is more accurate than the metric in Section E.7.1 because it does not include voids and air.
Disadvantages	• If not used along with additional information (eg type of material), it is difficult to identify areas where improvement can be effected.
Use	• Same as for the metric in Section E.7.1. • Barratt Developments.[209]

[204] BRE, 2012. *Waste Benchmark Data*. Available at: http://www.smartwaste.co.uk/filelibrary/benchmarks%20data/Waste_Benchmarks_for_new_build_projects_by_project_type_31_May_2012.pdf (Accessed: 20/05/2019).

[205] Bakshan, A., Srour, I., Chehab, G. and El-Fadel, M., 2015. A field based methodology for estimating waste generation rates at various stages of construction projects. *Resources, Conservation and Recycling*, *100*, pp.70-80.

[206] Lau, H. H., Whyte, A. and Law, P. L., 2008. Composition and characteristics of construction waste generated by residential housing project. *International Journal of Environmental Research,* 2(3): 261–268.

[207] Construction Resources & Waste Platform(CRWP), http://www.wrap.org.uk/sites/files/wrap/CRWPLeafletContractors.pdf (Accessed: 21/05/2019).

[208] Li, Y., Zhang, X., Ding, G. and Feng, Z., 2016. Developing a quantitative construction waste estimation model for building construction projects. *Resources, Conservation and Recycling*, *106*, pp.9-20.

[209] Barratt developments, https://www.barrattdevelopments.co.uk/sustainability/performance-data/performance (Accessed:21/05/2019).

E.7.3 Volume of waste/£100k

Volume/£100k	
Method of measurement	This metric is determined by dividing the volume of waste in m^3 produced during the on-site phase of a construction project by the total project value in £ multiplied by 100,000. Methods of measurement: as in Section E.7.1, but looking at project value rather than at the gross area.[210]
Merits and disadvantages	• As in Section E.7.1. • If not clearly stated, there can be confusion around the monetary value used for the normalization (eg capital, construction cost). This may make it difficult to compare like with like when the performance of different companies is considered.
Use	• As Section E.7.1. Examples of companies and organisations using this metric can be found in different sectors (eg housing[211], non-housing[212], etc.).

E.7.4 Weight of waste/£100k

Weight of waste/£100k	
Method of measurement	This metric is determined by dividing the weight of waste in tonnes produced during the on-site phase of a construction project by the total project value multiplied by 100,000. Examples of indicators obtained by normalising the tonnes of waste by using financial units different from £100k can be found in the literature; usually based on the country in which the project is located (eg tonnes/HK$m in ref 213). Methods of measurement: as in Section E.7.2, but looking at project value rather than at the gross area.
Merits and disadvantages	• As Section E.7.2.
Use	• As Section E.7.1.

E.7.5 Volume (or Weight) of waste per plot

Weight of waste/£100k	
Method of measurement	This metric is determined by dividing the volume (or weight) of waste produced during the on-site phase of a construction project by the number of plots within the considered construction site. Methods of measurement: as in Section E.7.2, but looking at the number of plots rather than at their gross area.
Merits and disadvantages	• As Section E.7.2.
Use	• Barratt Developments.

[210] UK Industry Performance Report 2018. Available at: http://constructingexcellence.org.uk/wp-content/uploads/2018/11/UK-Industry-Performance-Report-2017.pdf (Accessed: 28/03/2019).

[211] CLC, 2018. *Housing industry metrics.* Available at: http://www.constructionleadershipcouncil.co.uk/wp-content/uploads/2018/10 /Housing-Industry-Metrics-FINAL-191018.pdf (Accessed: 21/05/2019).

[212] Strathclyde University, https://www.strath.ac.uk/media/ps/estatesmanagement/recycling/ES_Contractor_Appointment_Appendix_Construction_Waste_New_Build_V1_1.pdf (Accessed: 21/05/2019).

[213] Lu, W., Chen, X., Peng, Y. and Shen, L., 2015. Benchmarking construction waste management performance using big data. *Resources, Conservation and Recycling*, *105*, pp.49-58.

E.7.6 Percentage of segregated material waste

Percentage of segregated material waste	

Method of measurement	This metric describes the percentage of material waste that is potentially available for recycling.
	Methods of measurement:
	• Indirect methods:
	  ◦ Using data from the waste management plan and/or financial data (eg invoices from companies dealing with the collection of recyclable materials, invoices for the disposal of waste).
	• Direct methods:
	  ◦ Direct observations carried out by an on-site dedicated observer measuring the quantities of segregated and non-segregated materials.

Merits	• Relatively simple to determine. • Used in conjunction with quantitative data (eg volume, weight) and quality data (ie material type) it becomes useful in determining the embodied carbon of a project[214].
Disadvantages	• Not directly related to strategic objectives. • May involve considerable effort and subjectivity in assessing volume or weight of different types of waste. • Requires space on site for placing dedicated skips. • An improvement in this metric can be achieved only by requiring the workforce to segregate waste.
Use	• Its use has been suggested by BRE.[215]

E.7.7 Amount of material waste to landfill

Amount of material waste to landfill	
Method of measurement	This metric, either expressed in m^3, in tonnes, or as a percentage of the total, can be obtained from a knowledge of the number and capacity of container loads sent to landfill.
Merits	• Simple to measure. • Objective, cost effective and verifiable. • Because landfill waste disposal has a cost and hence a financial impact, allows the management to clearly see the benefits of optimising the processes so that waste production can be minimised.
Disadvantages	• Related only partially to strategic objectives. • Requires each type of waste to be measured separately if improvements are to be effected. • Requires to be normalised against total GIFA or turnover or some other metric.
Use	• Used by WRAP and its NW Tool[216] and property developers such as Crest Nicholson[217] and Bovis Home Group PLC.[218]

[214] UK Green Building Council (UKGBC), 2015. Tackling embodied carbon in buildings. Available at: https://www.ukgbc.org/sites/default/files/Tackling%20embodied%20carbon%20in%20buildings.pdf (Accessed: 21/05/2019).

[215] BRE, 2009. *Benchmarks for Predicting and Forecasting Construction Waste - Annex 3*. Available on: randd.defra.gov.uk (Accessed: 21/05/2019).

[216] WRAP, 2012. *Net Waste Tool. User Guide, Version 1.0.* Available at: http://nwtool.wrap.org.uk/Documents/NW%20Tool%20Manual.pdf (Accessed: 21/05/2019).

[217] https://www.crestnicholson.com/about-us/integrating-sustainability/our-data (Accessed:21/05/2019).

[218] https://www.bovishomesgroup.co.uk/responsibilities/environment (Accessed: 06/06/2019).

E.7.8 Amount of material diverted from landfill

Amount of material diverted to landfill	
Method of measurement	This metric, either expressed in m^3, in tonnes, or as a percentage of the total, can be obtained as a direct measurement of the material diverted from landfill, or as a difference between the total amount of material waste and that portion sent to landfill.
Merits	• As Section E.7.7.
Disadvantages	• As Section E.7.6.
Use	• Used by contractors and house builders (eg Morgan Sindall[219]).

E.7.9 Percentage waste

Percentage waste	
Method of measurement	This metric was firstly developed in Brazil as part of a site monitoring research project[220]. It is defined as the amount of materials purchased by the company ($M_{Purchased}$) minus the material available in the inventory ($M_{Inventory}$) and the material '*defined by the measurement of work done*'[220]; all this divided by the material '*defined by the measurement of work done*' ($M_{Designed}$). $$Perentage\ waste = \frac{(M_{Purchased} - M_{Inventory}) - M_{Designed}}{M_{Designed}}$$
Merits	• Relates directly to strategic objectives. • Objective, understandable and verifiable. • Independent of design characteristics. • Relatively straightforward to calculate. • Can be applied at different levels: company level, project level, component level. • Provides useful information on where waste is occurring.
Disadvantages	• Does not provide indications on whether waste has been recycled or disposed. • No guidance provided on how "amount" should be measured.
Use	• Has been reported to be used in African countries (eg 221).

[219] Morgan Sindall, 2018. *Responsible Business Report 2018*. Available at: http://sustainability.morgansindall.com/~/media/Files/M/Morgan-Sindall-Sustainability/EC1051071_MSB_RBReport2018.pdf (Accessed: 06/06/2019).

[220] Formoso, C.T., Soibelman, L., De Cesare, C. and Isatto, E.L., 2002. Material waste in building industry: main causes and prevention. *Journal of construction engineering and management, 128*(4), pp.316-325.

[221] Oladiran, 2014. Construction professionals' perception of the awareness, application and benefits of material waste measurement techniques in Nigeria. *Proceedings of CIB conference 28th – 30th January 2014*, Lagos, Nigeria.

E.7.10 Tonnes/£m revenue

Tonnes/£m revenue	
Method of measurement	This metric is defined as the ratio of the tonnes of material waste produced to the revenue of a company expressed in £m.
Merits	• Reflects strategic objectives. • Simple to measure, objective and verifiable. • Has the capability to correlate financial and operational information.
Disadvantages	• Can only be applied at company level (ie not at construction site). • Does not provide granular information on the type of waste. • For a company involved in projects of different types and/or in different locations, revenue is not linearly proportional to the construction costs and hence to the quantity of material used. Accordingly, a change in this indicator cannot be considered with certainty as a symptom of a change in company performance.
Use	• We found only one example of companies using it: Balfour Beatty.[222]

[222] Balfour Beatty, 2018. Annual report, 2018. Available at: https://www.balfourbeatty.com/media/318113/balfour_beatty_annual_report_2018.pdf (Accessed: 21/05/2019).

APPENDIX F EMERGING TECHNOLOGIES

F.1. Preamble

A number of emerging technologies for determining some of the indicators discussed in this report were identified and reviewed. Generally speaking, each of these technologies is part of, or consists of a system with three components.

- Hardware for collecting data
- Software for processing and analysing the data collected
- Software for visualising data that has been processed and analysed

While each component has a single purpose (ie, collecting, processing, and visualizing the data), it can consist of more than one item. For example, in the case of a laser scanner mounted on a drone the hardware comprises the drone and the laser scanner.

The context in which the reviewed technologies are currently used is summarized in the following sections. Each shares the common structure outlined in Figure F 1. Information on their application for determining and sometimes improving the performance indicators listed in this study are also presented.

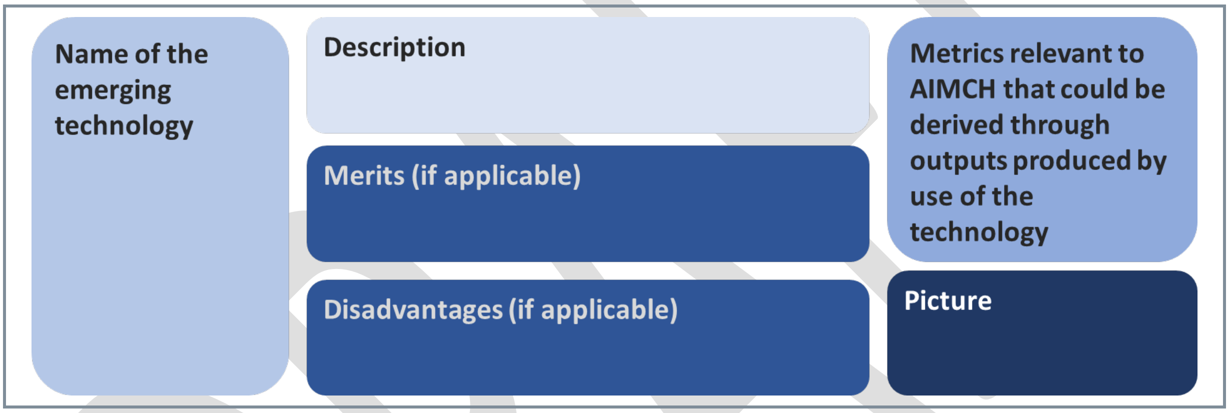
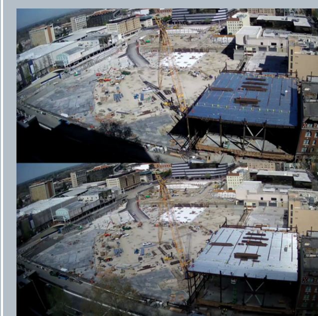


Figure F 1. Structure for describing the reviewed emerging technologies.

F.2. Reviewed emerging technologies

Digital tool / emerging technology	Notes/Description	Metrics relevant to AIMCH that could be derived through outputs produced by use of the technology
Time-lapse digital photography	Time-lapse photography records a slow process by taking a series of pictures at a constant time interval. Once played in sequence, these pictures provide an accelerated video of the process. It is often used for adding so called semantic information to geometric models so that data regarding the material the object is made of can be embedded in the model[223]. By coupling this information with the programme schedule of a project, it is possible to determine the actual construction stage of a given component[224,225]. The possibility of using time-lapse images to create an augmented reality has also been suggested[226]. **Merits** • Mature technology (eg solar powered cameras, data transferred through 3G network, Wi-Fi or satellite signal). • Widely used for site monitoring, marketing purposes and avoiding disputes.[227] • Commercial solutions are available.[227,228,229,230,231] • Relatively cheap (Timelapseuk[230] offers a camera for 18 months at a price of £368). **Disadvantages** • Anything hidden by scaffolding or moving machinery is not correctly recorded. • As it is currently used, it does not provide real-time data.[232] • Very difficult to extract data useful for managing a project if used as a standalone technology. To be effective it should be coupled to 3D, 4D BIM models[223,233] or project schedules. • Bespoke software is required if the user wants to automate the coupling of data collected through time-lapse photography and the programme of a project. Although examples of such software can be found in the literature (ie PHOTO-NET II[234]), they are limited to action-based research cases.	**Time** • Project schedule variation (%) • Schedule growth (%) • Project schedule factor  Ref. 235

[223] Han, K.K. and Golparvar-Fard, M., 2015. Appearance-based material classification for monitoring of operation-level construction progress using 4D BIM and site photologs. *Automation in construction*, *53*, pp.44-57.

[224] Dimitrov, A. and Golparvar-Fard, M., 2014. Vision-based material recognition for automated monitoring of construction progress and generating building information modeling from unordered site image collections. *Advanced Engineering Informatics*, *28*(1), pp.37-49.

[225] Yang, J., Park, M.W., Vela, P.A. and Golparvar-Fard, M., 2015. Construction performance monitoring via still images, time-lapse photos, and video streams: Now, tomorrow, and the future. *Advanced Engineering Informatics*, *29*(2), pp.211-224.

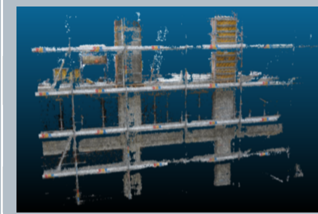
[226] Golparvar-Fard, M., Peña-Mora, F., Arboleda, C.A. and Lee, S., 2009. Visualization of construction progress monitoring with 4D simulation model overlaid on time-lapsed photographs. *Journal of computing in civil engineering*, *23*(6), pp.391-404.

[227] https://evercam.io/ (Accessed: 06/06/2019).

[228] https://www.c-site.eu/en/ (Accessed: 06/06/2019).

[229] https://www.time-lapse-systems.co.uk/ (Accessed: 06/06/2019).

[230] https://www.timelapseuk.com/ (Accessed: 06/06/2019).

Digital tool / emerging technology	Notes/Description	Metrics relevant to AIMCH that could be derived through outputs produced by use of the technology
Photogrammetry + BIM	Photogrammetry is a ‘*measurement technique to extract the geometry, displacement, and deformation […] using photographs or digital images*’[236]. If used in conjunction with the BIM model of a building it allows comparison of the as-built with the as-planned. When adopted during construction, photogrammetry and BIM allow the progress of a project to be tracked. Photogrammetric point clouds are used to describe as-built elements which are then compared to the scheduled ones taken from a BIM model. **Merits** • Mature technology widely adopted in different sectors (eg archaeology[237], civil engineering[236, 238]). • Relatively cheap technology. • Automated image processing is available. **Disadvantages** • Image processing can be time consuming and hidden elements are not captured. • Because image processing is affected by lighting conditions, errors can occur.	**Time** • Project schedule variation (%) • Schedule growth (%) • Project schedule factor **Quality** • Yield • Number and type of items that did not pass visual inspection  Ref. 239

[231] https://www.site-eye.co.uk/sectors/construction/ (Accessed: 06/06/2019).

[232] Matthews, J., Love, P.E., Heinemann, S., Chandler, R., Rumsey, C. and Olatunj, O., 2015. Real time progress management: Re-engineering processes for cloud-based BIM in construction. *Automation in Construction*, *58*, pp.38-47.

[233] Golparvar-Fard, M., Peña-Mora, F., Arboleda, C.A. and Lee, S., 2009. Visualization of construction progress monitoring with 4D simulation model overlaid on time-lapsed photographs. *Journal of computing in civil engineering*, *23*(6), pp.391-404.

[234] Abeid, J., Allouche, E., Arditi, D. and Hayman, M., 2003. PHOTO-NET II: a computer-based monitoring system applied to project management. *Automation in construction*, *12*(5), pp.603-616.

[235] Han, K.K. and Golparvar-Fard, M., 2017. Potential of big visual data and building information modeling for construction performance analytics: An exploratory study. *Automation in Construction*, *73*, pp.184-198.

[236] Baqersad, J., Poozesh, P., Niezrecki, C. and Avitabile, P., 2017. Photogrammetry and optical methods in structural dynamics–a review. *Mechanical Systems and Signal Processing*, *86*, pp.17-34.

[237] Nicolae, C., Nocerino, E., Menna, F. and Remondino, F., 2014. Photogrammetry applied to problematic artefacts. *The International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, *40*(5), p.451.

[238] https://leica-geosystems.com/en-gb/products/3d-imager/leica-blk3d (Accessed: 30/05/2019).

[239] Tuttas, S., Braun, A., Borrmann, A. and Stilla, U., 2014. Comparision of photogrammetric point clouds with BIM building elements for construction progress monitoring. *The International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences, 40(3),* p.341.

Digital tool / emerging technology	Notes/Description	Metrics relevant to AIMCH that could be derived through outputs produced by use of the technology
3D laser scanner + BIM	3D laser scanners allow the acquisition of 3D point clouds and are usually used for producing as-built models of existing assets [240,241] or construction sites[242]. Their use can be coupled with a BIM model in which case they can be considered an alternative to photogrammetry. The number and type of metrics that can be obtained by adopting this technology depend heavily on the information stored in the BIM model. **Merits***[243]* • Highly accurate measurements obtained in a relatively short time. • Data collection is not sensitive to lighting conditions. • Examples of automated overlaying of BIM models and laser scanner data can be found in the literature. **Disadvantages[243]** • Laser scanners are expensive and, as for photogrammetry, they require a clear line of sight for correctly capturing each component. • Overlaying of laser scanned images and BIM models, and comparison with project schedule is limited to case-based research.	**Time** • Project schedule variation (%) • Schedule growth (%) • Project schedule factor **Cost**[244] • Cost variance  Ref. 245

[240] Jung, J., Hong, S., Jeong, S., Kim, S., Cho, H., Hong, S. and Heo, J., 2014. Productive modeling for development of as-built BIM of existing indoor structures. *Automation in Construction*, *42*, pp.68-77.

[241] Barazzetti, L., Banfi, F., Brumana, R., Roncoroni, F. and Previtali, M., 2016. BIM from laser scans… not just for buildings: NURBS-based parametric modeling of a medieval bridge. In *XXIII ISPRS Congress, Commission V* (pp. 51-56).

[242] El-Omari, S. and Moselhi, O., 2011. Integrating automated data acquisition technologies for progress reporting of construction projects. *Automation in Construction*, *20*(6), pp.699-705.

[243] Omar, T. and Nehdi, M.L., 2016. Data acquisition technologies for construction progress tracking. *Automation in Construction*, *70*, pp.143-155.

[244] Turkan, Y., Bosché, F., Haas, C.T. and Haas, R., 2012. Toward automated earned value tracking using 3D imaging tools. Journal of construction engineering and management, 139(4), pp.423-433.

[245] https://www.bdcnetwork.com/5-tech-trends-transforming-bimvdc (Accessed 05/07/2019).

Digital tool / emerging technology	Notes/Description	Metrics relevant to AIMCH that could be derived through outputs produced by use of the technology
Automated Defect Recognition (ADR) + Deep learning techniques	ADR is a technology adopted for detecting defects on the surface and/or in the structure of a component (eg anomalous porosity, cracks). It usually requires a tool for the collection of the input data – which can be in the form of a digital photograph of the object or, for example, radiographic image – and an algorithm for processing the image and extracting information on anomalies and defects. Cases in which ADR has been used in conjunction with a deep learning algorithm can be found in the literature. This kind of algorithm can be used for training the software in identifying defects. ADR is widely adopted in the automotive industry. Examples of application in the construction sector have been reported in the i3p project[246] and can be found in the oil and gas industry.[247] **Merits** • Non-invasive and non-destructive investigation technique. **Disadvantages** • Bespoke solutions are usually required[246] based on item type and the material it is made of.	**Quality** • Yield • Number and type of items that did not pass visual inspection  Ref.247

[246] i3p, 2018. *Inspection for Construction and Infrastructure i3P discovery project poster*. Available at: http://www.the-mtc.org/construction-and-infrastructure/i3p-project (Accessed: 30/05/2019).

[247] https://news.developer.nvidia.com/ai-drones-help-inspect-industrial-equipment/ (Accessed: 30/05/2019).

Digital tool / emerging technology	Notes/Description	Metrics relevant to AIMCH that could be derived through outputs produced by use of the technology
Drones	Drones are unmanned aircraft systems that can be remotely controlled or fly autonomously through software-controlled flight plans.[248] When equipped with cameras, drones can be used for inspecting those components and/or parts of assets positioned at height whose integrity is difficult to assess because they are difficult to reach. When equipped with laser scanners they can be a viable tool for surveying and checking progress in construction. Examples of airborne laser scanning systems can be found in mining and forestry.[249] **Merits** • Mature technology. • Overcomes physical barriers and minimises risks connected to inspection/surveying in dangerous environments. **Disadvantages** • Can be expensive. • Limitations due to CAA regulations[250] (eg the item must always be in sight[251]).	**Time**[249, 252] • Project schedule variation (%) • Schedule growth (%) • Project schedule factor **Quality** • Yield • Number and type of items that did not pass visual inspection  Ref. 253

[248] https://internetofthingsagenda.techtarget.com/definition/drone (Accessed: 10/07/2019).

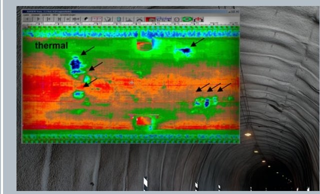
[249] https://www.3dlasermapping.com/riegl-uav-laser-scanners/ (Accessed: 18/06/2019).

[250] https://www.caa.co.uk/Commercial-industry/Aircraft/Unmanned-aircraft/Small-drones/Regulations-relating-to-the-commercial-use-of-small-drones/ (Accessed: 18/06/2019).

[251] https://www.nottinghamshire.police.uk/advice/drone-law-uk (Accessed: 18/06/2019).

[252] i3p, 2018. *Inspection for Construction and Infrastructure i3P discovery project poster.* Available at: http://www.the-mtc.org/construction-and-infrastructure/i3p-project (Accessed: 30/05/2019).

[253] https://www.3dlasermapping.com/riegl-ricopter/ (Accessed: 10/07/2019).

Digital tool / emerging technology	Notes/Description	Metrics relevant to AIMCH that could be derived through outputs produced by use of the technology
Infrared thermography	Infrared thermography detects infrared energy emitted from objects and converts it to temperature. An image of temperature distribution is displayed[254]. In construction, infrared thermography is commonly used for detecting non-visible defects in concrete structures[255] and for infrastructure inspections[256]. It has the potential to be used during the construction stage for detecting areas where insulation has not been properly set up and rework is required. **Merits** • Non-invasive and non-destructive technique. **Disadvantages** • Reading influenced by environmental conditions or external factors (eg leaves can affect readings while investigating a roof[257]).	**Quality** • Yield • Number and type of items that did not pass visual inspection  Ref. 258

[254] http://www.infrared.avio.co.jp/en/products/ir-thermo/what-thermo.html (Accessed: 10/7/2019).

[255] i3p, 2018. *Inspection for Construction and Infrastructure i3P discovery project poster.* Available at: http://www.the-mtc.org/construction-and-infrastructure/i3p-project (Accessed: 30/05/2019).

[256] Garrido, I., Lagüela, S. and Arias, P., 2018. Infrared thermography's application to infrastructure inspections. *Infrastructures, 3(3),* p.35.

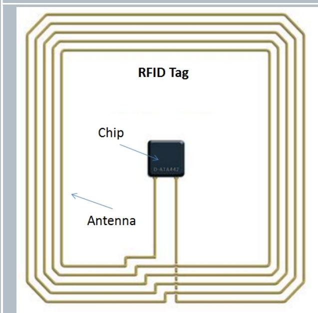
[257] https://www.techwalla.com/articles/the-disadvantages-of-thermography (Accessed: 18/06/2019).

[258] https://www.tunntech.com/index.php/technology-news/item/247-use-of-thermal-imaging-to-detect-hidden-damages (Accessed: 10/07/2019).

Digital tool / emerging technology	Notes/Description	Metrics relevant to AIMCH that could be derived through outputs produced by use of the technology
Real Time Locating Systems (RTLS) [259, 260]	Real Time Locating Systems (RTLS) is an umbrella term encompassing a multitude of technologies that allow an object (or human) to be located within an instrumented environment and its movement to be tracked[260]. RFID and UWB fall into this category of technologies. Each has its own pros and cons. Because RTLSs allow real-time movement of people and goods to be tracked, they can be used for collecting data for: improving safety on site (eg identifying any worker within a hazardous zone), estimating inputs used for calculating labour productivity metrics (ie, worked hours), minimizing time required to locate materials and tools, and so on. **Merits** • Discussed separately for each technology that can be classified as an RTLS – see items below. **Disadvantages** • Discussed separately for each technology that can be classified as an RTLS – see items below.	(See items below)

[259] Grau, D., Caldas, C.H., Haas, C.T., Goodrum, P.M. and Gong, J., 2009. Assessing the impact of materials tracking technologies on construction craft productivity. *Automation in construction*, *18*(7), pp.903-911.

[260] Li, H., Chan, G., Wong, J.K.W. and Skitmore, M., 2016. Real-time locating systems applications in construction. *Automation in Construction*, *63*, pp.37-47.

Digital tool / emerging technology	Notes/Description	Metrics relevant to AIMCH that could be derived through outputs produced by use of the technology
RFID tags[261, 262]	RFID (acronym for Radio Frequency Identification Device) is an example of an RTLS. An RFID tag consists of a chip for storing information and an antenna. Stored information can be read by portable devices as well as fixed readers. Three types of RFID tags exist[263]: • **Passive tags** are small and cheap RFID tags which are not powered by an external power source. They emit a signal only when activated by the electromagnetic waves generated by a reading device. They can be read only within a small range from the reader if in line of sight (usually less than 15 m). • **Active tags** are connected to an external power source. This allows them to actively emit a signal which can be received by a reader up to 500 m away. Active tags are bigger, more expensive and require more maintenance than passive tags. • **Hybrid tags** are similar to active tags, but instead of emitting a signal continuously, they do it only when activated by a satellite signal. **Merits** • Mature and relatively cheap technology. • Can serve different purposes (eg as a safety management tool by tracking workers' location and identifying those who are not wearing appropriate PPE[264, 265, 266, 267], for recording time spent on-site by a given worker or for tracking the location of a prefabricated component and hence infer information on the project schedule[268, 269, 270]). **Disadvantages** • Accuracy – between 0.3 m and 30 m depending on the type of environment, the presence of obstacles, the radio frequency used, the age of the tags and the location algorithm used.[271] • Need to be coupled to additional locating systems (eg GIS, GPS).[263] • Maintenance costs (only for active and hybrid tags).[263]	**Productivity** • Labour hours per plot  Ref. 272

[261] Valero, E., Adán, A. and Cerrada, C., 2015. Evolution of RFID applications in construction: A literature review. *Sensors*, *15*(7), pp.15988-16008.

[262] Zhang, L. and Atkins, A.S., 2015. A decision support application in tracking construction waste using rule-based reasoning and RFID technology. *International Journal of Computational Intelligence Systems*, *8*(1), pp.128-137.

[263] Omar, T. and Nehdi, M.L., 2016. Data acquisition technologies for construction progress tracking. Automation in Construction, 70, pp.143-155.

[264] LO, N.H. and LIN, Y.C., 2013, September. Enhancing Worker Onsite Safety Management Using Rfid Technology In Construction. In *Proceedings of the Thirteenth East Asia-Pacific Conference on Structural Engineering and Construction (EASEC-13)* (pp. B-3). The Thirteenth East Asia-Pacific Conference on Structural Engineering and Construction (EASEC-13).

[265] Teizer, J., 2016. Right-time vs real-time pro-active construction safety and health system architecture. *Construction Innovation*, *16*(3), pp.253-280.

[266] https://www.rfidjournal.com/articles/view?17115 (Accessed: 14/06/2019)

[267] https://gaorfid.com/people-locating-rfid-system/ (Accessed: 14/06/2019)

[268] Grau, D., Caldas, C.H., Haas, C.T., Goodrum, P.M. and Gong, J., 2009. Assessing the impact of materials tracking technologies on construction craft productivity. *Automation in* construction, *18(7),* pp.903-911.

[269] Zhong, R.Y., Peng, Y., Xue, F., Fang, J., Zou, W., Luo, H., Ng, S.T., Lu, W., Shen, G.Q. and Huang, G.Q., 2017. Prefabricated construction enabled by the Internet-of-Things. *Automation in Construction*, *76*, pp.59-70.

<table>
<tr><th>Digital tool / emerging technology</th><th>Notes/Description</th><th>Metrics relevant to AIMCH that could be derived through outputs produced by use of the technology</th></tr>
<tr><td rowspan="2">UWB tags</td><td rowspan="2">UWB (acronym for Ultra-Wide Band) is a RTLS technology. UWB tags are very similar to RFID tags but they work on different frequencies and over longer ranges. Unlike RFID systems, an UWB system allows the 3D position of the object to which it is connected to be determined. As a result, USB tags have been used for tracking the construction progress of pipeline works[273, 274, 275].

Merits
• More accurate than RFID (up to 0.3m accuracy).
• Reading range up to 150m.

Disadvantages[276]
• Expensive.
• Interference can affect accuracy.
• Battery powered tags may have to be charged frequently, depending on the chosen product.</td><td>Productivity
• Labour hours per plot</td></tr>
<tr><td>
Ref. 277</td></tr>
</table>

[270] https://www.tensor.co.uk/construction-cscs-card/ (Accessed: 14/06/2019)

[271] Li, H., Chan, G., Wong, J.K.W. and Skitmore, M., 2016. Real-time locating systems applications in construction. *Automation in Construction*, *63*, pp.37-47.

[272] https://www.analogictips.com/rfid-tag-and-reader-antennas/ (Accessed:10/07/2019).

[273] Shahi, A., Aryan, A., West, J.S., Haas, C.T. and Haas, R.C., 2012. Deterioration of UWB positioning during construction. *Automation in Construction*, *24*, pp.72-80.

[274] https://www.sewio.net/reduce-lead-time-in-make-to-order-production/ (Accessed: 14/06/2019).

[275] Omar, T. and Nehdi, M.L., 2016. Data acquisition technologies for construction progress tracking. *Automation in Construction, 70*, pp.143-155.

[276] https://be-smart.io/blog/difference-between-rfid-vs-uwb-vs-ble/ (Accessed: 14/06/2019).

[277] https://www.sewio.net/product/piccolino-tag/ (Accessed: 10/07/2019).

Digital tool / emerging technology	Notes/Description	Metrics relevant to AIMCH that could be derived through outputs produced by use of the technology
BLE tags	BLE (acronym for Bluetooth Low Energy) is a RTLS technology which is very similar to UWB tags. Unlike RFID systems, a BLE system allows the 3D position of the object to which it is connected to be determined. **Merits**[278] • Batteries can last years. • Easier to deploy than RFID. • Tags are cheaper than UWB. **Disadvantages**[278] • Less precise than UWB (accuracy of the order of 2-3 m) • Radio interferences can affect accuracy and stability of the connection.	**Productivity** • Labour hours per plot  Ref. 279

[278] https://be-smart.io/blog/difference-between-rfid-vs-uwb-vs-ble/ (Accessed: 11/07/2019).
[279] https://kontakt.io/blog/kontakt-io-bluetooth-tag-s18-3/ (Accessed: 11/07/2019).

Digital tool / emerging technology	Notes/Description	Metrics relevant to AIMCH that could be derived through outputs produced by use of the technology
Augmented reality (AR) and Virtual reality (VR)	Augmented reality (AR) 'is an environment wherein virtual and real world are combined to enhance users' experience of the virtual world through contextual information. It gives the user the ability of observing the background environment and superimposes a virtual model over the real-world background'[280]. In other words, VR allows real-time comparison of 3D models with physical spaces.[281] AR differs from Virtual reality (VR) because the latter 'removes the user from the real-life environment around them and immerses them into an entirely computer-generated environment'[282]. In the construction sector AR usually comprises superimposing as-planned information/models on the as-built through an app. It has the potential to help to identify quality related issues[283, 284, 282, 285]. VR is usually used for visualizing 3D models, identifying design-related issues, and has the potential to be a useful tool in safety training. [286, 287, 288, 289, 290] **Merits** • Apps are available and are relatively cheap. **Disadvantages**[275] • The level of maturity (for its use as as-planned/as-built comparison) is below the average.[282] • Expensive. • Requires the generation of BIM models. • Might require the generation of a BIM model through laser scanning the as-built environment. • Not widely adopted in the construction sector.	**Quality** • Yield • Number and type of items that did not pass visual inspection  Ref. 291

[280] Golparvar-Fard, M., Peña-Mora, F., Arboleda, C.A. and Lee, S., 2009. Visualization of construction progress monitoring with 4D simulation model overlaid on time-lapsed photographs. *Journal of computing in civil engineering*, *23*(6), pp.391-404.

[281] https://connect.bim360.autodesk.com/construction-technology-innovation-2019 (Accessed: 10/07/2019).

[282] i3p, 2018. *VR, AR and MR*. Available at: http://www.the-mtc.org/construction-and-infrastructure/i3p-project (Accessed: 30/05/2019).

[283] https://www.maptek.com/news/maptek-brings-augmented-reality-to-the-mining-industry/ (Accessed: 14/06/2019).

[284] https://bimanywhere.com/index.php (Accessed: 14/06/2019).

[285] http://www.the-mtc.org/our-case-studies/immersive-visualisation-for-collaborative-construction-projects (Accessed: 18/06/2019).

[286] Sacks, R., Perlman, A. and Barak, R., 2013. Construction safety training using immersive virtual reality. *Construction Management and Economics*, *31*(9), pp.1005-1017.

[287] Li, X., Yi, W., Chi, H.L., Wang, X. and Chan, A.P., 2018. A critical review of virtual and augmented reality (VR/AR) applications in construction safety. *Automation in Construction*, *86*, pp.150-162.

[288] https://workersafety.3m.com/welcome-world-virtual-reality-safety-training/ (Accessed: 18/06/2019).

[289] https://www.vrsafety.co.uk/our-stuff/ (Accessed: 18/06/2019).

[290] https://www.vrsense.com/en/index.php/product/vrsense-safety-hazards-construction/ (Accessed: 18/06/2019).

[291] https://www.bdcnetwork.com/augmented-reality-goes-mainstream-12-applications-design-and-construction-firms (Accessed: 10/07/2019).

APPENDIX G STUDIES SUGGESTED BY AIMCH PARTNERS

G.1. Preamble

As part of the commission we were asked to take cognizance of the following “studies”:

- AIMC4
- BRE Construction Lean Improvement Programme (CLIP)
- BRE SMARTWaste
- BRE CALIBRE
- MTC i3P

Information sharing the common structure outlined in Figure G 1 has been produced for each suggested study. Not all the considered studies focus on collecting data for determining performance: some of them (eg BRE CLIP) aim to improve them.

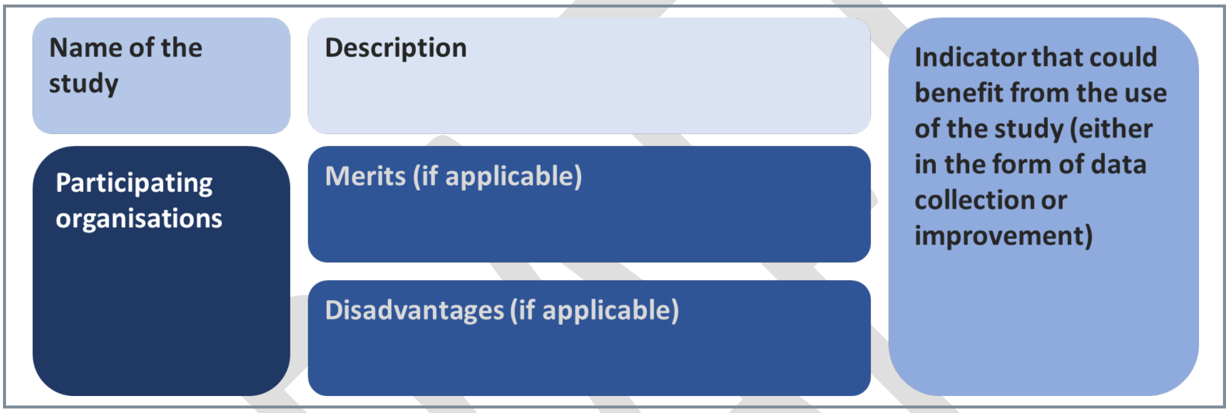


Figure G 1. Structure of the information describing the suggested studies.

Name of the study, project or tool	Notes/Description	Indicators that could benefit from the adoption of AIMC4 principles			
AIMC4	AIMC was a consortium aiming to build innovative homes compliant with level 4 of the Code for Sustainability. Members of the consortium were: Stewart Milne Group, Barratt Developments PLC, Crest Nicholson PLC, H+H UK Ltd and Oxford Brookes University.[292] Some of the objectives were: • to develop low carbon homes[293] • to adopt new technologies for delivering cost-effective building solutions[293] • to improve sustainability by using offsite manufacture methods. (ie increase energy efficiency, improve efficiency of the supply chain and reduce build costs).[294]	**Safety**	✓ 294	**Time**	✓ 295
		Labour productivity	✓ 294,295	**Predictability**	
		Quality	✓ 293,294	**Efficiency**	
		Cost	✓ 294, 295	**Material waste**	✓ 295
Stewart Milne Group Barratt Developments PLC Crest Nicholson PLC H+H UK Ltd BRE	The project consisted of three key stages[295]: • **Pre-construction stage**: during this stage lean thinking principles were implemented in the design process through BRE CLIP. The final design was hence the result of an iterative process that involved designers, supply chain and developers' construction teams. • **Construction phase**: during the construction phase BRE CALIBRE was used to measure productivity, material waste, quality, embodied carbon, H&S, non-value-added time, costs. • **Post-Construction phase:** during this phase the performance of the as-built assets was evaluated. A 12-month post-occupancy study was carried out at the end of this.				

[292] http://www.stewartmilne.com/AIMC4_sustainable_homes.aspx (Accessed: 14/06/2019).

[293] https://www.designcouncil.org.uk/sites/default/files/asset/document/DC%20CABE%20HOUSING%20CASE%20STUDY_2_AIMC4_310316%20FINAL.pdf (Accessed: 14/06/2019).

[294] CLC, 2018. *AIMC4 Casestudy*. Available at: http://www.constructionleadershipcouncil.co.uk/wp-content/uploads/2018/10/181022-CLC-Casestudy-AIMC4.pdf (Accessed: 14/06/2019).

[295] Cartwright, P., Gaze, C., Tilford, A. and Corfe, C., 2013. *Lessons from AIMC4 for cost-effective, fabric-first, low-energy housing IP 9/13*. Available at: https://www.brebookshop.com/details.jsp?id=327195 (Accessed: 14/06/2019).

<table>
<tr><th>Name of the study, of the project or of the tool</th><th>Notes/Description</th><th colspan="4">Indicators that could benefit from the adoption of BRE CLIP</th></tr>
<tr><td rowspan="4">BRE CLIP</td><td rowspan="5">CLIP (Construction Lean Improvement Programme) is a management approach developed by BRE. Its aim is process improvement through the elimination of wasteful activities[296]. It can be applied both to on-site construction activities and those based in factories (eg manufacturing of components such as windows).[297]

In order to meet its objectives, CLIP Master Managers make use of lean principles and techniques such as process mapping, collaborative planning, visual management, the 5C approach (Clear out, Configure, Clean and Check, Conformity, Custom and Practice), the identification of the seven wastes associated with a process (ie transportation, inventory, motion, waiting, over-production, over-processing, defects).[302]

Merits
• Case studies show it can have an immediate impact on process efficiency and on the time required to complete a task.
• It can bring long term benefits to those companies that correctly implement lean management principles.

Disadvantages
• It is a licensed product.
• It requires a BRE CLIP Master Engineer.
• It might meet resistance from the workforce[301].
• Very few construction organisations have persisted sufficiently to embed lean principles across all their activities[298].</td><td>Safety</td><td>✓ 296</td><td>Time</td><td>✓ 296, 301</td></tr>
<tr><td>Labour productivity</td><td>✓ 296, 297,299</td><td>Predictability</td><td>✓ 302</td></tr>
<tr><td>Quality</td><td>✓ 297, 301, 300</td><td>Efficiency</td><td>✓ 296</td></tr>
<tr><td>Cost</td><td>✓ 296,301</td><td>Material waste</td><td>✓</td></tr>
<tr><td>More than 150 companies between 2006 and 2009[296] (eg J & S Seddon (Building) Ltd, Stepnell Ltd, Pearce Group Ltd, Cruden Construction Ltd, NG Bailey & Co Ltd, Thomas Vale Construction plc, Bluestone)[301,302].</td><td colspan="4"></td></tr>
</table>

[296] BRE, 2009. *What is CLIP?* Available at: https://www.bre.co.uk/filelibrary/pdf/CLIP/What_is_CLIP_-_20-07-09_Rev_3.pdf (Accessed 25/02/2019).

[297] BRE, 2006. *CLIP: Case Studies Vol 2. Profit Together from Process Improvement.* Available at: https://www.bre.co.uk/filelibrary/pdf/CLIP/BRE-_CLIP_Vol_2_reprint_2006.pdf (Accessed: 25/02/2019).

[298] Ward, S.A., 2015. *Critical Success Factors for Lean Construction* (Doctoral dissertation, The University of Dundee).

[299] Construction excellence, 2015. Lean construction Available at: constructingexcellence.org.uk/wp-content/uploads/2015/03/lean.pdf (Accessed: 25/02/2019).

[300] BRE, *Oakwood casestudy*. Available at: https://www.bre.co.uk/filelibrary/pdf/CLIP/KN3712_Oakwood_CS_v2.pdf (Accessed: 25/02/2019).

[301] BRE, *CLIP Casestudy Bluestone Buxton*. Available at: https://www.bre.co.uk/filelibrary/pdf/CLIP/Casestudy_Bluestone_Buxton.pdf (Accessed 25/02/2019).

[302] BRE, 2003. *CLIP: Case Studies Vol 1. Profit from Process Improvement.* Available at: https://www.bre.co.uk/filelibrary/pdf/CLIP/Vol_1__CLIP_Case_Study_Booklet_28-09-04.pdf (Accessed: 25/02/2019).

<table>
<tr><th>Name of the study, of the project or of the tool</th><th>Notes/Description</th><th colspan="4">Indicators that could benefit from the adoption of BRE SMARTWaste</th></tr>
<tr><td rowspan="4">BRE SMARTWaste</td><td rowspan="5">SMARTWaste is a web-based ‘Environmental site monitoring and reporting software’ produced by BRE[303]. It allows the management and reduction of waste outputs, their impact and the associated costs[304]. Site Waste Management Plans can be prepared and monitored through SMARTWaste.

The product consists of eight modules, each focused on a specific aspect of waste management:

• Construction Waste Management[305]: allows real-time monitoring of waste movements. It requires information on waste carrier IDs, destination IDs, container used IDs, volume and/or tonnage of waste, type of waste, waste management route, etc.

• Construction Site Water Management[306]: for monitoring water use, reuse, recycling and discharge. It requires quantitative information for each of these items to be collected on a weekly or monthly basis.

• Construction Site Energy Management[307]: for monitoring on-site generated CO_2 and consumed kWh. It requires qualitative and quantitative information on the amount of electricity, gas and fuel used. It allows benchmarking a specific project against the company or industry performance.

• Construction Site Transport Management[308]: for monitoring CO_2 emissions associated with waste and materials movement and disposal. It requires information on the number of journeys, the distance travelled, the amount of fuel consumed, the purpose of the journey (eg material delivery, waste disposal).</td><td>Safety</td><td></td><td>Time</td><td></td></tr>
<tr><td>Labour productivity</td><td></td><td>Predictability</td><td></td></tr>
<tr><td>Quality</td><td></td><td>Efficiency</td><td></td></tr>
<tr><td>Cost</td><td>✓</td><td>Material waste</td><td>✓</td></tr>
<tr><td>More than 10,000 users[309]. Canary Wharf Contractors Limited is one of them[310].</td><td colspan="4"></td></tr>
</table>

303 https://www.bresmartsite.com/products/smartwaste/ (Accessed: 25/02/2019).

304 https://www.designingbuildings.co.uk/wiki/BRE_SMARTWaste_online_reporting_platform (Accessed: 25/02/2019).

305 https://www.bresmartsite.com/how-we-help/waste-management/ (Accessed: 25/02/2019).

306 https://www.bresmartsite.com/how-we-help/water-management/ (Accessed: 25/02/2019).

307 https://www.bresmartsite.com/how-we-help/energy-management/ (Accessed: 25/02/2019).

308 https://www.bresmartsite.com/how-we-help/transport-management/ (Accessed: 25/02/2019).

309 https://www.bresmartsite.com/blog/it-all-starts-here-smartwaste-version-2-release/ (Accessed: 25/02/2019).

310 https://www.bresmartsite.com/blog/credible-data-driving-environmental-performance-improvements-2/ (Accessed: 25/02/2019).

Name of the study, of the project or of the tool	Notes/Description	Indicators that could benefit from the adoption of BRE SMARTWaste			
BRE SMARTWaste	• **Construction Material Management[311]:** for monitoring material supply and sustainability certification status. It requires information on the type of material, the existence of suppliers' certificates. • **Ecology and Biodiversity Management[312]:** for assessing the impact of a project on the local habitat. It helps fulfil BREEAM requirements. • **Reporting[313]:** for exporting information collected in the different modules and presenting results about specific KPIs. • **Other site impacts[314,315]:** for recording other project related metrics such as the number of incidents that have occurred, the results of internal and external audits and the number of staff hours.	**Safety**		**Time**	
		Labour productivity		**Predictability**	
		Quality		**Efficiency**	
		Cost	✓	**Material waste**	✓
More than 10,000 users[316]. Canary Wharf Contractors Limited is one of them[317].	**Merits** • Face-to-face training is provided by BRE. • Easy to learn. • Aligned to BREEAM principles. • It forces the company to think about the most appropriate material source and hence to interact with the supply chain since the early stage of the project if it is seeking a performance improvement. **Disadvantages** • It is a licensed product.				

[311] https://www.bresmartsite.com/how-we-help/materials-management/ (Accessed: 25/02/2019).

[312] https://www.bresmartsite.com/how-we-help/ecological-management/ (Accessed: 25/02/2019).

[313] https://www.bresmartsite.com/reporting/ (Accessed: 25/02/2019).

[314] https://www.bresmartsite.com/how-we-help/other-site-impacts/ (Accessed: 25/02/2019).

[315] BRE, 2018. *SmartWaste Release 7.3 webinar*. Available at: https://www.bresmartsite.com/webinars/ (Accessed: 17/06/2019).

[316] https://www.bresmartsite.com/blog/it-all-starts-here-smartwaste-version-2-release/ (Accessed: 25/02/2019).

[317] https://www.bresmartsite.com/blog/credible-data-driving-environmental-performance-improvements-2/ (Accessed: 25/02/2019).

Name of the study, of the project or of the tool	Notes/Description	Indicators that could benefit from the adoption of BRE CALIBRE			
BRE CALIBRE	CALIBRE is a *'construction process measurement tool'* based on time and motion studies carried out in UK in the 60s and 70s[318]. It aims to identify and eliminate waste by making combined use of the following[319,322]:	**Safety**		**Time**	✓ [321]
	• **Time Evaluation Assessment Measurement Systems (TEAMS):** time associated with the completion of an activity is divided into value adding time, support time, statutory time and non-added value time.	**Labour productivity**	✓ [319,322]	**Predictability**	✓ [322]
	• **BREPlan:** for capturing the predictability of a process. Predictability is here defined as:	**Quality**	✓ [319]	**Efficiency**	✓ [322]
	$\frac{\textit{Actual tasks started or complete this week}}{\textit{Tasks planned to be started or completed this week}}$	**Cost**		**Material waste**	✓ [322]
Companies from different sectors[322]: Railtrack, BAA, McDonalds, Slough Estates, MoD, Whitbread, ASDA/Wal-Mart, Sainsburys	CALIBRE is implemented in six phases: • Process mapping of all the activities taking place onsite • Identification and coding of all the tasks • Setting of benchmark values • Measuring • Analysing collected data • Questioning the reasons why those results were obtained. **Merits** • It requires a cultural change within the organization. • It has been proven to be effective in projects with a high M&E content and with a high degree of repeatability. **Disadvantages** • It requires workshops to be held by CALIBRE trainers. • It can be costly – due to the necessity of having full time observers on-site – and requires an *'excessive amount of information'*.[320]				

[318] BRE. *What is CALIBRE?* Available at: http://www.smartwaste.co.uk/filelibrary/calibre/what_is_calibre.pdf (Accessed: 25/02/2019).

[319] BRE, *CALIBRE The measurement of success*. Available at: http://projects.bre.co.uk/BREslam/download/1tmdbi9.pdf (Accessed: 17/06/2019).

[320] Oral, M. and Oral, E., 2007. A computer based system for documentation and monitoring of construction labour productivity. In *CIB 24th W78 Conference*.

[321] Winch, G. and Carr, B., 2001. Benchmarking on-site productivity in France and the UK: a CALIBRE approach. *Construction Management & Economics*, *19*(6), pp.577-590.

[322] Vassos, C., 2001. CALIBRE–The toolkit for facilitating world class performance in the UK construction industry. *CIB World Building Congress, April, Wellington, New Zealand, paper HPT 02*.

Name of the study, of the project or of the tool	Notes/Description	Indicators that could benefit from the adoption of technologies and methodologies reviewed by MTC i3P Discovery Phase 2 Projects			
MTC i3P Discovery Phase 2 Projects	MTC contributed to the funding of a series of projects during the Discovery Phase 2 of the i3p program. The aim of the funded projects was to establish the state of the art across the industries of a series of technologies whose implementation in the construction sector could help to meet the targets set in the Government's Construction 2025 Strategy[323]. Although a large amount of information on each one of the eight projects that have been completed to date can be found in summarising posters[323], only information relevant to the objectives of this research are discussed in detail here. In particular, information on how the cited technologies can be used for measuring indicators related to metrics listed on the right side of this table were considered.	**Safety**	✓	**Time**	✓
		Labour productivity	✓	**Predictability**	
		Quality	✓	**Efficiency**	✓
		Cost	✓	**Material waste**	
	Wearables for health, safety and wellbeing i3P discovery project poster[324] A variety of commercially available wearable devices and solutions aiming to minimize (or to draw attention to) the occurrence of injuries was reported and analysed. It is suggested that most of them (eg posture sensors, muscle activity sensors, vibration measuring, proximity sensors), could help to improve – directly or indirectly – safety on a construction site when adopted. Nevertheless, none of them can be used for determining the safety metrics listed in Sections 3.1 and E.1. Some of them, such as sensors recording vibration and postures might be repurposed and used for collecting information about time and value-added time. For example, after recording the posture or the movement pattern associated with a repetitive activity, it should be possible to determine how much time a given worker spent carrying it out. **Fixed asset sensing technologies**[325] Available technology for monitoring assets during the post-construction phase was reviewed. Overall, the project is out of the scope of this literature review.				

[323] http://www.the-mtc.org/our-projects/i3p-programme (Accessed: 25/02/2019).

[324] i3p, 2018. *Inspection for Construction and Infrastructure i3P discovery project poster*. Available at: http://www.the-mtc.org/construction-and-infrastructure/i3p-project (Accessed: 25/02/2019).

[325] i3p, 2018. *Asset Technology i3P discovery project poster.* Available at: http://www.the-mtc.org/construction-and-infrastructure/i3p-project (Accessed: 25/02/2019).

<table>
<tr><th>Name of the study, of the project or of the tool</th><th>Notes/Description</th><th colspan="4">Indicators that could benefit from the adoption of technologies and methodologies reviewed by MTC i3P Discovery Phase 2 Projects</th></tr>
<tr><td rowspan="4">MTC i3P Discovery Phase 2 Projects</td><td rowspan="5">Legacy data conversion[326]

This project explored ‘the process of using Legacy Data by construction firms and the problems they encounter when doing so’. With the exclusion of

• the use of laser scanners and BIM models for gathering and visualizing information regarding existing assets – which has been widely discussed in Appendix F,
• and the possibility of using legacy data for comparing the as-planned with the as-built.

This project is out of the scope of this literature review.

Robotics and automation[327]

This project reviewed the existing technology available in the field of robotics and automation and that is (or might be) applied in construction and that could lead to a productivity, quality and H&S improvement. In particular, the poster focused on 5 areas: hard automation, robotics, collaborative workspace, data capture and automated decision making, tele-operated technology.

Of the reviewed technologies, only drones could be used for collecting data and helping to determine the performance indicators considered in this project (see Section F.2 for more details).

Standardised component sets i3P discovery project poster[328]

The project reviewed all the aspects associated with the adoption of standardised components: construction materials, design management and build methods. For each one, a series of technologies were identified (eg volumetric, sub-assemble, kit of parts, traditional and standardized components for the “Bild methods”), and their pros and cons outlined.

Overall, the project is out of the scope of this literature review.

Lifecycle approach to data creation and management[329]

The project reviewed the importance of consistently collecting data across the whole life cycle of an asset and making collected data available to stakeholders that might require them.

Overall, the project is out of the scope of this literature review.</td><td>Safety</td><td>✓</td><td>Time</td><td>✓</td></tr>
<tr><td>Labour productivity</td><td>✓</td><td>Predictability</td><td></td></tr>
<tr><td>Quality</td><td>✓</td><td>Efficiency</td><td>✓</td></tr>
<tr><td>Cost</td><td>✓</td><td>Material waste</td><td></td></tr>
<tr><td></td><td colspan="4"></td></tr>
</table>

[326] i3p, 2018. *Legacy Data i3P discovery project poster*. Available at: http://www.the-mtc.org/construction-and-infrastructure/i3p-project (Accessed: 25/02/2019).

[327] i3p, 2018*. Use of robotics i3P discovery project poster*. Available at: http://www.the-mtc.org/construction-and-infrastructure/i3p-project (Accessed: 25/02/2019).

[328] i3p, 2018. *Standardised component sets i3P discovery project poster*. Available at: http://www.the-mtc.org/construction-and-infrastructure/i3p-project (Accessed: 25/02/2019).

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<tr><th>Name of the study, of the project or of the tool</th><th>Notes/Description</th><th colspan="4">Indicators that could benefit from the adoption of technologies and methodologies reviewed by MTC i3P Discovery Phase 2 Projects</th></tr>
<tr><td rowspan="4">MTC i3P Discovery Phase 2 Projects</td><td rowspan="5">VR, AR and MR[330]

This project aimed to ‘benchmark the maturity and applicability of VR, AR and MR throughout the [construction and infrastructure] industry’. This was done through examples of case-studies and qualitative considerations collected through surveys, stakeholders’ engagement and desk-top research.

Examples in which AR and VR are used for assessing the adherence of the as-built to the as-planned and as an effective tool for safety trainings are presented.

Inspection for construction and infrastructure[331]

The project ‘focuses on inspection for construction and infrastructure. It clarifies what technology is available, the benefits it could bring and the barriers to its adoption’[331]. Metrology and non-destructive testing methods applied to large assets, buried assets, underwater assets, hidden elements and manufactured elements were considered. Additionally, the management and use of inspection data was examined.

The use of visual inspection, laser scanners, drones, photogrammetry, thermography and ultrasound are cited among the technologies that could be used for carrying out inspections. The use of BIM is suggested for managing processed information. Details of the benefits associated with the use of these technologies can be found in Appendix F.</td><td>Safety</td><td>✓</td><td>Time</td><td>✓</td></tr>
<tr><td>Labour productivity</td><td>✓</td><td>Predictability</td><td></td></tr>
<tr><td>Quality</td><td>✓</td><td>Efficiency</td><td>✓</td></tr>
<tr><td>Cost</td><td>✓</td><td>Material waste</td><td></td></tr>
<tr><td>Who participated to the study, to the project or used the tool:</td><td colspan="4"></td></tr>
</table>

[329] i3p, 2018. *Lifecycle Approach to Data Creation and Management i3P discovery project poster*. Available at: http://www.the-mtc.org/construction-and-infrastructure/i3p-project (Accessed: 25/02/2019).

[330] i3p, 2018. *VRARMR i3P discovery project poster*. Available at: http://www.the-mtc.org/construction-and-infrastructure/i3p-project (Accessed: 25/02/2019).

[331] i3p, 2018. *Inspection for Construction and Infrastructure i3P discovery project poster*. Available at: http://www.the-mtc.org/construction-and-infrastructure/i3p-project (Accessed: 25/02/2019).