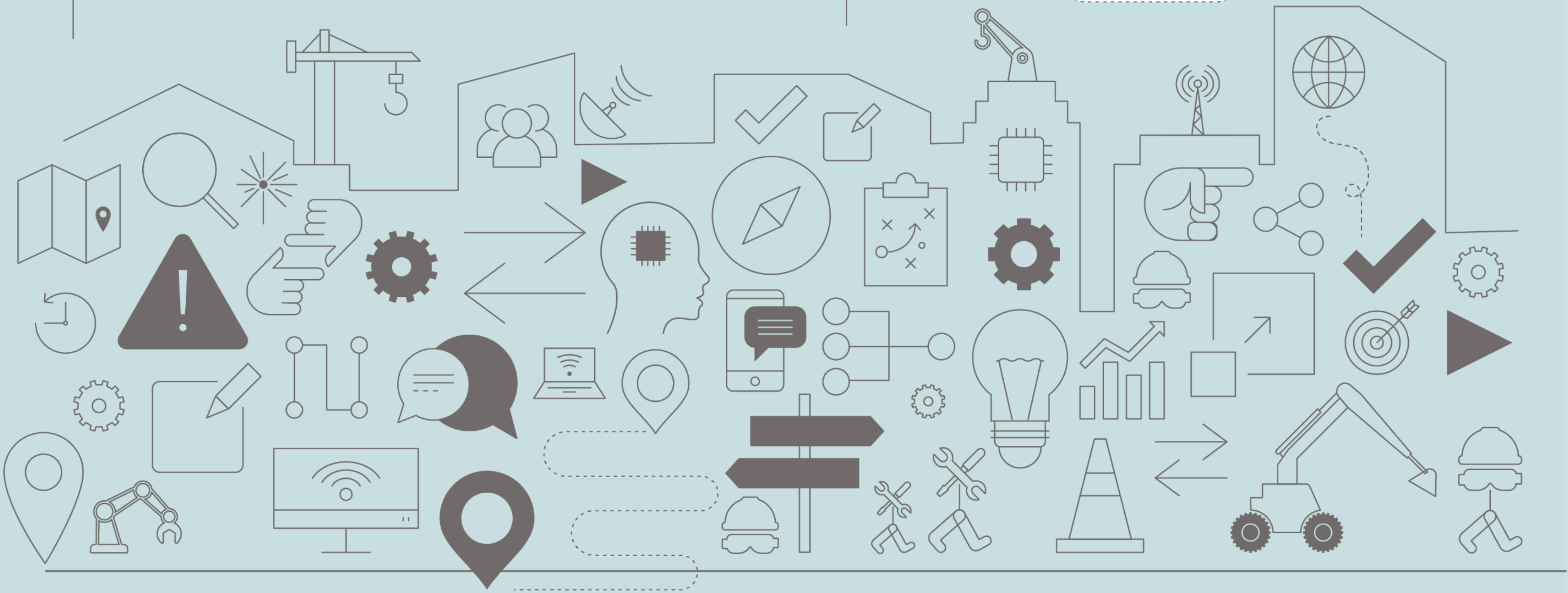
Connected and Autonomous Plant

Design for Machines



Executive summary

The National Highways roadmap for Connected and Autonomous Plant (CAP) (TRL, i3P and HE, 2020) identified a need for the design of highways construction to adapt, with the consumer of the design now potentially being an automated system (Machine Control) instead of a human. It was suggested that the processes to transfer the necessary information for construction from the design model to the Machine Control system require improvement, to achieve the objective of "Design for Machines".

To identify the current challenges to achieving Design for Machines, a series of engagement workshops were conducted with stakeholders from across the Design for Machines ecosystem. This included representatives of engineering design companies, earthworks contractors, Tier 1 contractors, survey companies and technology providers. This revealed many of the challenges faced by different parties in the design and construction process relating to Design for Machines.

The consultation identified challenges with the Design for Machines process that fall into two broad categories: technical issues with the outputs of design models, and wider issues with the organisation of the design and construction feedback loop. The stakeholder engagement process has also identified a number of potential solutions to overcome these barriers, leading to the following recommendations:

Within 2 years:

1. **There should be a national specification for models intended for the production of earthworks using Machine Control**. This should be a set of layers (a grouping of related design information, typically lines, in the model) which have a defined naming and colour scheme. The naming and colour scheme should prioritise accessibility for operators who will be interacting with the Machine Control. Common drawing issues for Machine Control such as misalignment at interfaces between subassemblies, or an unnecessary number of nodes, should be absent from models delivered to this standard. A suggested basis for this standard is described in this report and should be incorporated into GG 184 (NH et al., 2020).

2. **There should be greater use of tolerances in design models**, particularly where there is known uncertainty. This is to enable earthworks contractors to adapt the design model to the true site characteristics but in a controlled way which ensures that the desired engineering outcome is achieved.

3. **A digital rehearsal should be undertaken to test all systems through which design files will pass, in which all stakeholders in the chain should participate.** This will identify issues in the model or with data transfer processes so they

can be proactively fixed before all design work is complete and, potentially, problems embedded.

Within 10 years:

4. **A single digital design model should be shared with all parties involved in the construction. This should be the single source of truth for the design.** This would replace the current system of cascading the design models through different contractors. This will require a major change to current working practice but will remove discrepancies between the design model and the real world. It will overcome the key barriers to both Machine Control and the use of CAP in the wider construction process. Although, the adoption of a single shared digital model will require major changes to the current way of working, and new roles and responsibilities, it has the potential to simplify the currently disjointed process.

Although Machine Control is an early example of automation in construction, addressing the issues with designing for machines will help overcome the barriers to bringing higher levels of automation in future systems. Hence implementing these recommendations may be important to encouraging transition to routine use of Connected and Autonomous Plant (CAP), as set out in the CAP Roadmap and National Highways long-term strategic plan to 2050 (NH, 2023).

We would like to thank all participants who generously shared their knowledge and experience during the stakeholder engagement. We would particularly like to thank Sam Lemon and MJ Church for sharing their modelling standard.

List of acronyms

Acronym	Definition
2D	2 Dimensional
3D	3 Dimensional
3DMC	3D Machine Control
4D	4 Dimensional
BIM	Building Information Modelling
CAD	Computer Aided Design
CAP	Connected and Autonomous Plant
CW	Carriageway
DMRB	Design Manual for Roads and Bridges
DTM	Digital Terrian Model
FD	Finished Design
FGL	Finished Ground Level
GNSS	Global Navigation Satellite System
IMU	Inertial Measurement Unit
LHS	Left-Hand Side
NMU	Non-Motorised Users
OGL	Original Ground Level
PD	Pond and Ditches
QA	Quality Assurance
RHS	Right-Hand Side
SI	Site Improvement
TIN	Triangular Irregular Network
VRS	Vehicle Restraint System

Contents

Introduction

It is anticipated that the introduction of automated processes to the construction sector, via the implementation of Connected and Autonomous Plant (CAP), will bring benefits including improved productivity, quality, safety, welfare and reduced cost. However, the implementation of this new approach presents a significant challenge to the wide range of stakeholders across the construction sector.

To understand the steps required for CAP to be fully adopted, National Highways commissioned the CAP roadmap in 2019 (TRL, i3P and HE, 2020), which drew on extensive consultation with industry partners across the CAP ecosystem. The roadmap details many components and pieces of work which will be required to enable CAP adoption, and to ensure it is utilised to its full potential.

A key challenge identified in the roadmap was that, as Connected and Autonomous Plant (CAP) adoption increases, the design of highways construction will need to adapt to account for the consumer of the design now being an autonomous system instead of a human. This application of the design to (semi) automate the construction process is commonly referred to as Machine Control and has begun to be widely adopted on National Highways construction sites.

However, the current processes to transfer the necessary information for construction from the design model to the Machine Control system is laborious and often manual. There is the potential for significant improvement in this process. The key objectives of this work have been to better understand these challenges and identify potential improvements in the process, to support "Design for Machines".

CAP and CAP adoption

In this work we consider CAP to be construction machinery for which some or all of the movement or operation is controlled or assisted by non-human means (the autonomous component). Data or instructions can be transferred to or from the plant via digital communications to assist the operation (the connected component). In the near term, CAP is generally focused on systems to assist the human operator. The drivers for adopting CAP in this role include:

- **Reducing operator workload.** Systems such as 3D Machine Control (3DMC) or automatic grade control can provide contextual information, assist with controlling movement or take control of one part of operations. This reduces the demands placed on the operator and allows them to concentrate on other parts of the task.
- **Replacing physical setting out.** Machine Control systems can present the design to be constructed to the operator,

relative to the position of the machine. This can replace the traditional requirement for physical markings placed on site.

- **Increasing quality and reducing errors.** It is typically claimed that the precise guidance from Machine Control systems increases the quality of construction. Increasing quality and reducing errors reduces rework.
- **Reducing people/plant interactions.** Machine Control systems reduce or eliminate the need for manual measurements to be taken during earthworks operations, reducing the need for workers to be in close proximity to machines, and reducing a major cause of accidents.
- **Obtaining as-built information from plant.** Sensor information from CAP can be used to measure what has been constructed and augment or replace separate surveys.
- **Datalogging the work conducted.** The sensor information from CAP can also be used to record what has been done. For example: fuel consumed, volume moved, or idle time.

It is anticipated that automated plant movement and operation will increase over time, leading to full automation. Advantages of this would include:

- **Assisting with operator shortages.** Plant operators are an ageing workforce and recruitment to maintain the number of operators required is challenging (CITB and Experian, 2023).
- **Removing workers from site.** Plant that does not require an operator reduces the number of scenarios where people can be injured. For example, walking across uneven ground and climbing into machines. Interactions between people and plant can become the exception rather than a common occurrence.
- **Enabling continuous operation.** Automated systems can operate as long as required within site or plant maintenance limits.

Machine Control

Machine Control is the most widely used CAP system. This is a collection of systems which know the position of the plant and its functional components (e.g. for an excavator, the position of its arm and bucket, or for a grader, the height of its blade) in 3D space. This is achieved through Global Navigation Satellite Systems (GNSS), Inertial Measurement Units (IMU) and sensors measuring actuator position. Additional information is supplied to the Machine Control system from the design that is being constructed. The position of the plant compared to the design can then be determined, which is then used to inform the operator and provide them with assistance. This might be via simply displaying the design relative to the plant on a screen or via active assistance such as enforcing excavation depth limits or automatic grade control.

An operator is always involved when using Machine Control. Whilst Machine Control is an important component in the transition to automation, the deployment of Machine Control on construction plant does not result in that item of plant having a high level of automated capability. For example, the autonomous capability framework developed by National Highways (TRL, Costain, i3P and NH, 2022) applies a five part classification assessing plant in areas such as observation, decision making and carrying out actions – with levels from 0 to 4 (for some of the classifications). A typical 3DMC system would be classified as 11010 in this framework, which describe lower levels of automated capability.

Machine Control is now mandated on all National Highways construction projects (HE, 2021). However, the CAP roadmap found that, although Machine Control is an important step to automation, a number of issues were limiting its use. These issues are primarily associated with challenges to efficiently transferring design information from design models to Machine Control systems. The causes of the issues are complex and span both organisational and technical contexts. These issues are discussed in detail throughout this report.

Design for Machines

In the current design process, engineering design companies create a design model of the scheme to be constructed. The design model contains a large amount of information, including that required for construction, future asset management requirements, quantity calculations, and carbon calculations. Many of these requirements for the model are set in the Design Manual for Roads and Bridges (DMRB).

A Tier 1 contractor is appointed to construct the project. In most cases the Tier 1 contractor will subcontract parts of the work. For example, the earthworks will be conducted by a specialist earthworks subcontractor. The design model passes through this chain and is received by (e.g.) the earthworks subcontractor.

Currently a large amount of work is required to translate the information from the design model into inputs suitable for Machine Control (the reasons for this are discussed in detail in the later sections of this document). To undertake the translation, a cottage industry has emerged to "flip" the design from one software or system to another. This step is technically difficult because it requires knowledge of multiple Computer-Aided Design (CAD), drawing management and Machine Control software, and there is the potential to cause unintentional changes to the model. This step has great potential to be automated and streamlined.

To address this, there will be a need for the design process to better consider the end user as an operator using Machine Control. This is known as Design for Machines. For this to become an efficient process, the design model must be created such that it can be consumed by Machine Control without major modification. Any changes made to the design model would be for engineering reasons, not data transfer reasons. However, legitimate reasons to make changes to the design model will remain. For example, an earthworks subcontractor may wish to incorporate temporary works into the design which were not known about at the design stage.

Delivering this project

To understand the current challenges and barriers facing Design for Machines, and to identify solutions to these issues, a series of workshops were conducted with stakeholders from across the design and construction ecosystem. This included stakeholders from engineering design companies, earthworks contractors, Tier 1 contractors, survey companies, Machine Control technology providers and design software providers. Further details of the stakeholders are provided in *Appendix B Stakeholder acknowledgements*.

Three events were held with stakeholders. The first, a workshop, concentrated on the challenges and barriers. The second, a further workshop, continued this discussion with a focus on possible solutions to the challenges and barriers. The final event was a demonstration, where Machine Control best practice was shown, and feedback was gathered on the identified solutions. Throughout these events, cross industry conversation was encouraged so that different parties could gain understanding of the challenges others faced. Further details of the events, and the key findings from each, are provided in *Appendix A Methodology*.

Report outline

The consultation identified key challenges to Design for Machines within two themes: *Outputs appropriate for design for machines,* which covers technical issues with the outputs of design models relating to Machine Control; and *The design feedback loop,* which covers wider issues with the organisation of the design and construction feedback loop. The sections of this report focus on these themes. Within each, a summary is presented of the challenges and barriers within the theme area, and the implications of these for Design for Machines. Recommendations relating to actions that could be taken to overcome the barriers are then presented. Case studies are also provided to help place the proposed actions into context of current good practice.

It should be noted that the stakeholder engagement was predominately conducted with earthworks in mind. This is because earthworks construction is where Machine Control is most widely used, and is where its use has been mandated by National Highways. Therefore, the examples in this report are based on earthworks, but they will be relevant to other users of Machine Control, such as pavements subcontractors.

Outputs appropriate for design for machines

In a smooth Design for Machines process, the process to transfer the necessary information from the design model to the Machine Control system would be automatic, and not require human intervention or interpretation. Currently this is not the case and large amounts of human effort are required to extract the necessary information and rework parts of the design model to enable it to be used by Machine Control. In this section we discuss the challenges and needs identified through the stakeholder engagement.

Challenges

Inconsistent contractor requirements

Stakeholders from the design community felt the design information required for earthworks construction varied between different earthworks subcontractors. To ensure the design model is created in a way suitable for Machine Control, consistency in the information required is desirable. This is so that processes for creating the information can be defined and the relevant components and layers can be checked. Therefore, the current inconsistency is a barrier to automation.

Stakeholders from the earthworks community felt that there were no major obstacles to having a consistent set of requirements as long as flexibility was retained to deviate from this if the design required it.

Poor consistency and accessibility for operator

The DMRB document GG 184 (NH et al., 2020) specifies the use of CAD for National Highways construction projects. GG 184 dictates a naming scheme for components including the lines and layers in the model. The naming scheme is complex. It contains codes which are required for usage of the design model in Building Information Modelling (BIM). However, when the model is loaded into a device for Machine Control, the complexity of these layer names creates major accessibility issues for the operators. These include:

- **Length of name.** The layer name can be too long to display well on the Machine Control screen, which is typically a small tablet style device. This in not helped by the descriptive elements of the layer name being at the end of the name and therefore the most likely bit to be hidden from view. This makes it difficult to select the correct layer which discourages use of the Machine Control and increases the probability of the wrong layer or line being selected.

- **Inconsistent descriptive names.** The descriptive elements of the layer name differ between companies due to different naming conventions for the same thing. This can cause confusion for the operator when selecting the correct layer.
- **Unnecessary information.** Most of the layer name is not relevant to the operator and only acts as a barrier to identifying the necessary layer.
- **No logic to the sort order.** Most Machine Control devices will display layers in alphabetical order. The alphabetical order of the current layer names will bear no relation to the grouping of the layers for the task being conducted. To make navigation of the Machine Control device easier, operators would benefit from a sort order which is related to the task at hand.

The lines and surfaces from the model can be displayed on the Machine Control, with colour coding being supported on many devices. However, the optimal choice of colours will have been determined by the designer to aid them in making the design. They will not be optimised for the subset of information from the model that is required by the operator during a specific construction task, and therefore may not be intuitive to interpret during construction. There are also other limitations, such as Machine Control devices typically not supporting complex line styles (e.g. dotted and dashed lines).

In both naming schemes and colours, there is no consistency between different design companies. Therefore, the operator will be presented with different looking designs with different naming schemes, layer names and colour schemes on different projects. This means no consistent understanding of the displayed design can be obtained by the operator and their past experience may be misleading for the current construction project. This limits the information they can obtain from the Machine Control. The consultation found that this is a source of frustration which discourages the use of Machine Control. This is compounded by many operators being subcontracted individuals themselves. They will only work on a project for a short time before moving to the next site. This will further reduce their familiarity with the layer names and colour schemes. This lack of consistency (standardisation) also makes it very difficult to develop a Machine Control operator training syllabus.

Design model complexity and size

Current design models are typically large and complex. Reasons for this include:

- High resolution point cloud data from the site are used to create parts of the model, leading to a large number of polygons in the model. This significantly increases file size, which is a challenge for design software, Machine Control software and file transfer processes.

- BIM, material and carbon requirements being stored in the model for use in other work.
- High resolution polygons being included to support visualisation or animation in other uses of the model.
- The model for the overall design can be split into subassemblies which are smaller models containing different parts of the overall design. For example, slip roads and a roundabout may be different subassemblies.

The size and complexity of the design models causes many issues when using them in Machine Control. The first issue is that the file size of the design model may be too large to be loaded onto the Machine Control device. Whilst the design model is created using workstation computers, Machine Control devices have limited computing power because they are small and portable devices.

The recent trend is for design models to incorporate more subassemblies. A subassembly will be stored in its own file and therefore the overall design will contain many files. Subassemblies are used to enable simultaneous working by designers or to manage file size or limitations in design software. The subassemblies increase the complexity of navigating the design, particularly if using different software to the one in which the design was created. Each subassembly may be versioned independently, which can compound navigation challenges.

Issues with the alignment of lines at the interfaces between subassemblies are regularly reported. This is where two parts of the model should mate perfectly but do not. This is because they have been created separately in different subassemblies and are not quite the same. Even with no alignment issues, the presence of interfaces breaks the continuity of lines that are effectively one line. Both are issues for Machine Control which will interpret the alignment issues as a real discontinuity (e.g. a step) in the earthworks. Machine Control also cannot connect lines where there is an artificial break between subassemblies. These issues require human intervention to address, either by the operator or to the design model before it is loaded onto the Machine Control device.

The complexity of the design model, particularly if it has subassemblies, makes it difficult to navigate to extract the required subset of layers for a task. This can be an issue for an engineer, employed by the earthworks subcontractor, working with the model offsite. For example, they might be preparing a model for Machine Control use and using a powerful desktop computer. It can be a greater issue if this is not addressed before the model is used on–site. In this case, the operator will be presented with a bewildering array of options and be asked to select the correct one. This is whilst having a limited understanding of the overall design and only a small tablet with limited computing power to navigate upon. This is not helped by Machine Control being a relatively recent innovation, of which many operators have limited experience and minimal or no training, which may be further compounded by language or literacy barriers.

Design software has moved to use 3D volumes rather than lines. This has many benefits for other applications of the design model, but Machine Control devices currently work best with simple linework as inputs. The focus on volumes has removed the focus from linework and the needs of contractors, causing quality issues with the linework. For example the issues at interfaces between subassemblies discussed above or triangulation which does not well represent the geometry. Current design models and the software ecosystem struggle to cater for the diverse differences in detail of information required by their diverse use cases. It is currently a challenge to tailor models to specific uses.

The design model will contain details of the whole design, which can lead to confusion when undertaking the earlier stages of the construction process, such as earthworks. For example, the design model may contain many lines relating to kerbs. However, earthworks subcontractors only require the back of kerb and edge of carriageway to construct this part of the earthworks. The presence of other lines for kerb is unnecessary information and can lead to the wrong line being selected during construction.

Design models do not always consider the method and feasibility of construction. For example, formations may be heavily optimised to reduce the use of expensive materials. However, it may not be possible to construct such a geometry using typical construction machinery because the changes in layer thickness are too frequent and beyond the capability of the machine.

Design model replacing on site setting out

One advantage of using Machine Control is that it can replace setting out the site with physical paint and markers by an engineer. This removes the need to conduct a task but also causes a change in responsibility which can cause challenges. Machine Control replaces setting out by showing the operator the design of what they are constructing on the device in the cab, rather than them relying on setting out markers. The implication of this is the designers who created the model are now responsible for setting out. This is despite it being unlikely that they will visit the site and therefore lack the insight that can be gained from the real site at the phase of construction of the activity. This can lead to discrepancies between the model and the site which need to be addressed. This is discussed further in *Assumptions at the beginning of the design process*.

Implications

Major rework by subcontractor

As a result of the challenges described above, there is typically an unavoidable requirement for major rework of the design model to enable it to be used for Machine Control.

On receipt of the design model, the earthworks subcontractor will refine large parts of the model so it can be successfully loaded onto Machine Control and to make the information provided to the operator more useful and easier to use. This rework can take weeks of time. The work primarily consists of identifying and extracting a simple set of information that is suitable for both Machine Control and interpretation by the operator, changing how it is presented so it is accessible to the operator, and finding and fixing issues which the Machine Control cannot handle. These may be caused by issues with the design (e.g. unsuitable triangulation or interface issues) or differences between the design and site (e.g. differences identified on the site or compared to more recent survey information). Parts of the work on the model may be conducted concurrently with construction activities.

Beyond the time and cost, this process has other implications. Because small changes to the model are required to make it work for Machine Control, the subcontractor changes the design and therefore effectively takes on some responsibility for the design risk. This is not a responsibility the current process intends them to take on. However, they decide to take on this risk rather than take erroneous or inaccurate design information to site, which may slow production or cause mistakes and the need for rework.

When designs are updated and reissued, this rework may need to be repeated.

Inconsistency between models

There is a risk of inconsistency when redrawing or reconstructing parts of the design. For example, different software will approach surface triangulation in different ways. Therefore, small discrepancies can occur. These effectively change the design, and hence present risks to the quality of the design risk and quality of the construction. This can also create multiple versions of the truth which can cause confusion.

Recommendation: A standardised set of layers, layer colours and layer names for a task

Timescale: Within 2 years

There should be a national specification, incorporated into GG 184, for models intended for the production of earthworks using Machine Control. This should define the lines and layers, and their names and colours. This definition should cover all the information needed to conduct common earthworks tasks with Machine Control. The layer names and colours should be set with operator accessibility in mind. Therefore, layer names should be short and related to the task. They should be grouped by task for easy navigation. They should not contain unnecessary information. The linework should be continuous from a construction point of view. The node count in the line work should be minimised as much as is practicable without compromising the geometry.

This set of requirements is not intended to be limiting. It can be expanded where necessary. Expansion should be done in consultation with all parties involved in that task.

During this project, a good practice approach to defining these requirements was identified and is presented as a case study in the following section of this report. It is recommended that the approach taken in the case study is adopted as the recommended common set of information delivered from the design model for earthworks in GG 184 during its current review. This approach should be built upon for other stages of the design and construction process, e.g. pavements.

Adopting this recommendation would improve the data transfer process by establishing for all parties the common set of layers that they will either need to create or will be available to them to consume. This consistency has many advantages:

- It enables automation of processes throughout the data transfer chain.
- Having the same look and naming convention presented to operators across projects and between earthworks firms, which prioritises accessibility, will reduce the familiarisation burden for a workforce with a high turnover.
- It will enable consistent training packages to be developed for staff throughout the design and construction chain because of the standardisation of the design and information requirements.

Once adopted as a specification, the set of layers and the naming and colour scheme should become a deliverable from the design process. Once it is a specific asset, then it can be checked against the requirements for quality by the designer internally. They would not need to wait for downstream feedback, as is often currently the case. Aspects that would need to be checked would include interface continuity, minimised node count, no unnecessary layers, and conformance to the colour and naming scheme.

Case study: MJ Church modelling standard

MJ Church, a civil engineering and earthworks contractor, have developed an internal modelling standard for the designs that they push to Machine Control. The standard includes definitions for the layer names and the colours the lines in those layers are set to. The models are used for both Machine Control and setting out.

The priorities when defining the standard were:

- **Simplicity.** The layer list was minimised and unnecessary or misleading linework is removed from the source design model. The aim is to only use one line if one line is sufficient for the task.
- **Grouping.** Related layers are grouped together by the numbered naming scheme so they will correctly group when sorted alphanumerically. This means the grouping will persist across different Machine Control and setting out devices because all devices can sort via this method.
- **Specificity.** The model for Machine Control is created with its intended use in mind. Layers are only included if they represent the geometry that will be constructed during the task that the specific model is for.
- **Standardisation.** Consistency in the layering, colour and general 'feel' of the models across all of MJ Church's drawings creates a familiar environment for the machine

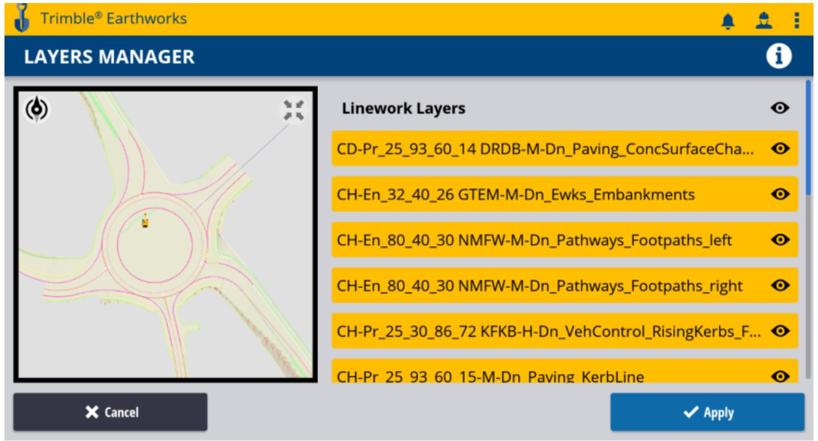


Figure 1: Layer names shown on a Machine Control device which are too long to display, have a complex naming scheme, and are poorly organised and fragmented.

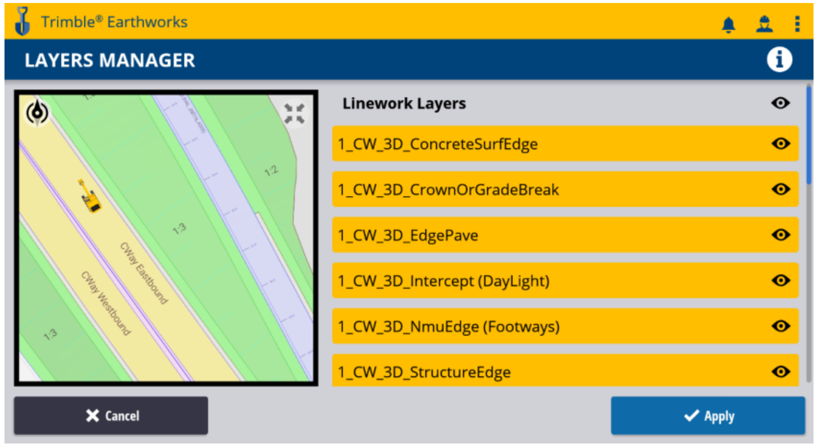


Figure 2: Layer names shown on a Machine Control device which are following the MJ Church colour and naming scheme.

operators to work within. Training can be built upon this consistent approach.

- **Communication.** The models make use of colour, text and non–verbal indicators of intent (e.g. arrows, slope line indicators/tadpoles) to clearly explain the design and provide non–ambiguous visualisations.

The list of layers for carriageways is shown in Table 2. As can be seen, the first character in the layer name is a number, and this character dictates the alphanumeric sorting and thereby grouping. All carriageway layers begin with 1. Other numbers are used for different purposes such non–corridor based models, alignments, intermediate formations, drainage, and avoidance zones. The numbering and grouping of the colour and naming scheme is shown in Table 1. The sorting and standardisation allow easy navigation of the layers for either engineers or operators.

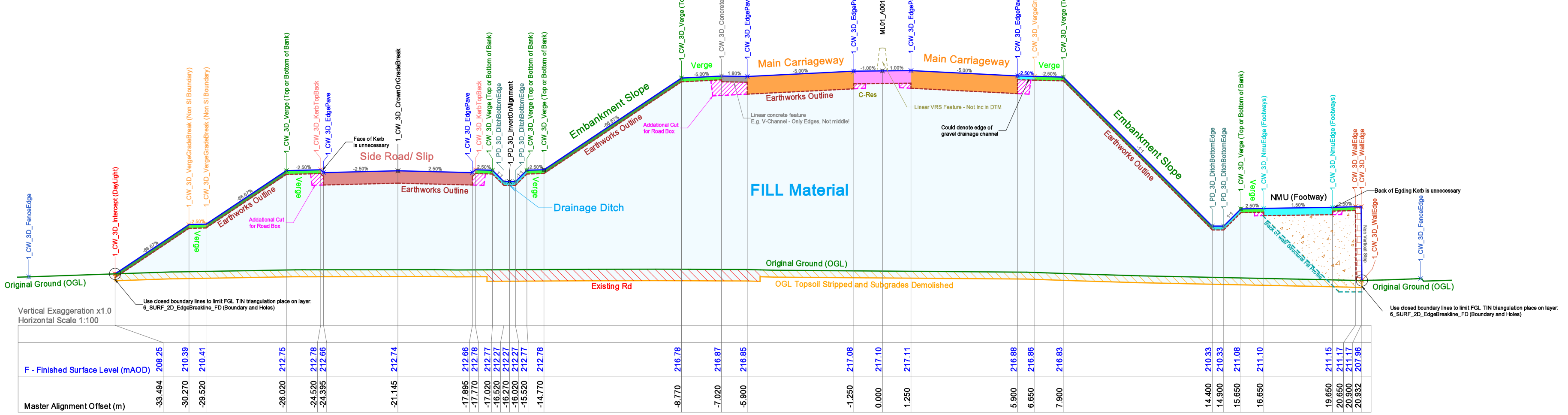
Table 1: The layer grouping from the MJ Church layer name and colour scheme.

Layer group	Description
1_CW_...	Carriageways
1_PD_...	Ponds and ditches
2_SOPs_...	Setting out points, typically used by engineers
2_SITE_...	Layers used for all non–linear base modelling such as car parks, industrial developments and pads
2_SP_...	Stockpiles
2_SUB_...	Subgrade surface
3_CORR_...	Corridor templates
3_HAL_...	Horizontal and vertical alignments
4_PREP_...	Side slope
5_INT_...	Intermediate surfaces
5_TOF_...	Takeoff
6_SURF_...	Surface information
7_MASS_...	Mass haul information
8_ANNO_...	Annotation
9_REV_...	Model revision records
A1_AVOID_...	Avoidance zones
A2_OGL_...	Original Ground Level
A3_Drainage Design...	Drainage
A4_IMAGE_...	Image data
A9_UNUSED_...	Erroneous or unneeded information

Figure 3 (overleaf): Example cut and fill sections using the MJ Church modelling standard. What will be shown in Machine Control is similar to the 3D views.

TIN Surface Cross Section Legend - Surfaces Used for Machine Control & Take-off

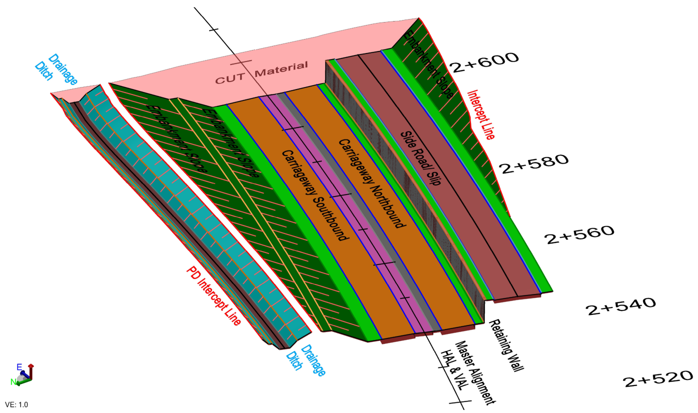
- F - Finished Surface Level (Top of Tarmac, Top of Topsoil, Ect)
- B - EW Formation (Underside of Capping, Earthworks Profile) - VERTICAL OFFSET
- B - EW Formation With Horrizontal Offsets Fully Modelled
- Original Ground Survey (OGL)
- Original Ground with Topsoil Stripped and Subgrades Demolished



Standard 3D Linework Used to Create A Typical FILL Embankment Section - CH 1+800

3D View of Typical CUT Embankment Section

- Linestring Colours as per drawing legend (standardised layers)
- Surfacing Colours project specific (ref pavement layout / landscape drawings)



Drawing Objective

This drawing presents the standard layers and 3D linework used for the construction of a typical carriageway Finished Ground Level (FGL) TIN (Triangular Irregular Network) model. These models will be used for machine control and setting out purposes.

The presented MJ Church 3D modelling standards prioritise:

Simplicity – Realised with a stripped-back layer list and datasets that are purged of unnecessary and erroneous linework. Don't use 3 lines when 1 will do.

Grouping – Relevant layers are grouped together and named in such a way that no matter the system they end up being used in they will be sorted alphanumerically in a general order of importance.

Specificity – Task specific, as Earthworks specialists we must build our 3D models with their intended use in mind. The purpose is not to include every possible feature that could ever exist in a road corridor but instead to accurately represent the geometry that will practically be constructed during a certain task.

Standardisation – An aligned approach to the use of layering, colour and the general 'feel' of models creates a familiar environment for our machine operators to work within. Training can be built around this unified approach.

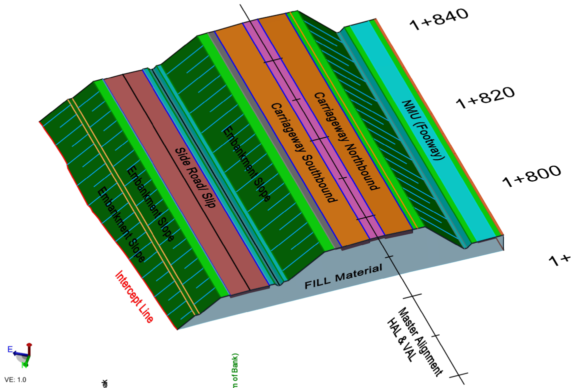
Communication – Appropriate use of colour, text and non-verbal indicators of intent (arrows, slope line indicators/ tadpoles)

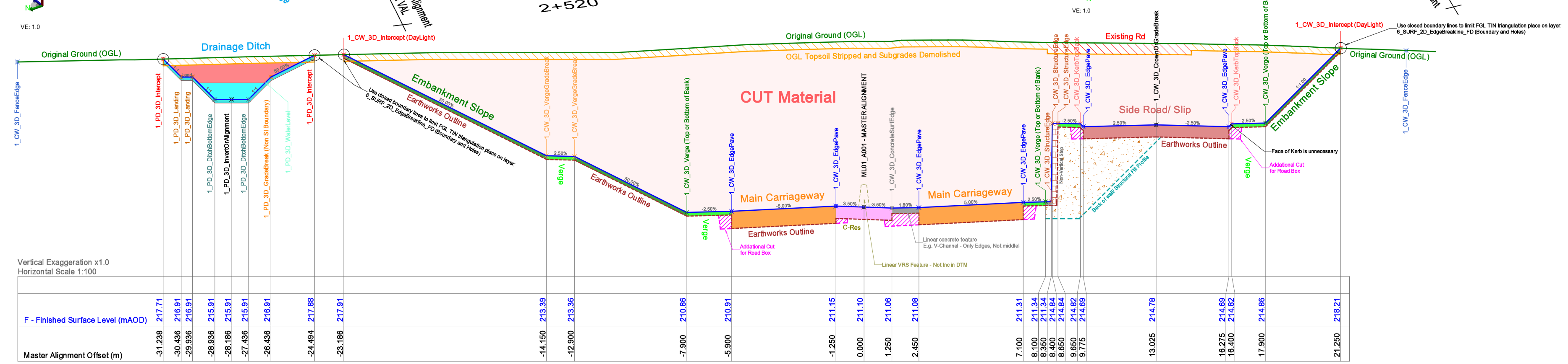
Construction efficiency and carbon reduction aspirations may be realised by implementing the above. Using these specified layers is a step towards this vision.

Templates have been developed for all the major DTM software modelling packages, contact engineering services for access to these resources.

3D View of Typical FILL Embankment Section

- Linestring Colours as per drawing legend (standardised layers)
- Surfacing Colours project specific (ref pavement layout / landscape drawings)





Standard 3D Linework Used to Create A Typical CUT Embankment Section - CH 2+600

Notes:

1. All dimensions shown are in meters unless otherwise stated.
2. Do not scale from this drawing. All dimensions are to be checked and verified on site.
3. This drawing is to be read in conjunction with all relevant supplementary documents/ engineers notes were specified.
4. The locations of any known services shown on the drawing are approximate and for guidance only, unless explicitly stated/ co-ordinated.
5. Site hazards my be present yet not stated on the drawing, consult contractual drawings to understand all relevant site hazards and risks.

Carriageway (CW) 3D Linework Legand

Forms Finished Level Surface (TIN)

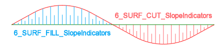
- 1_CW_3D_ConcreteSurfEdge
- 1_CW_3D_CrownOrGradeBreak
- 1_CW_3D_EdgePave
- 1_CW_3D_Intercept (DayLight)
- 1_CW_3D_KerbTopBack
- 1_CW_3D_NmuEdge (Footways)
- 1_CW_3D_StructureEdge
- 1_CW_3D_Verge (Top or Bottom of Bank)
- 1_CW_3D_VergeGradeBreak (Non SI Boundary)
- 1_CW_3D_WallEdge

For REF

- 1_CW_3D_FenceEdge
- 1_CW_3D_RoadMarkings
- 1_CW_3D_VRS (Resistant Systems)

**NOTE - Linework Layers Can Be Turned OFF/ ON In The Trimble Earthworks, Layer Manager. Accessed from the "Spade and Gear Icon" - Bottom Right

Embankment Slope Profiles



Pond and Ditches (PD) 3D Linework Legand

Forms FGL (TIN)

- 1_PD_3D_DitchBottomEdge
- 1_PD_3D_Feature (Wall or Structure)
- 1_PD_3D_GradeBreak (Non SI Boundary)
- 1_PD_3D_Intercept
- 1_PD_3D_InvertOrAlignment
- 1_PD_3D_Landing
- 1_PD_3D_WaterLevel

**NOTE - Linework Layers Can Be Turned OFF/ ON In The Trimble Earthworks Layer Manager. Accessed from the "Spade and Gear Icon" - Bottom Right

Reference Grid:	Reference Datum:
IAN 99/07 Local Grid A15 (For Example)	ODN Newlyn Datum Geoid: OSGM15

All Dimensions in Metres

Notes:

REV:	DESCRIPTION:	BY:	DATE:
V01	Linestring node markers added, 3D images added	SL	09/02/2024
V02			
V03			

STATUS: INFORMATION

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CLIENT:

SITE: A Typical Highways Site

TITLE: MJ Church 3D Linework Layer Naming Standards for FGL Machine Control Models

SCALE AT A1:	DATE:	DRAWN:	CHECKED:
1:100	01/12/2023	SLemon	SLemon

PROJECT NO:	DRAWING NO:	REVISION:
STANDARD	REF-001	V01

Table 2: The MJ Church layer name and colour scheme for carriageways.

Layer Name	RGB Colour			Colour preview	Line Type	Line Weight	Exported to 3DMC?	Comment on Usage
01 – CARRIAGEWAYS 3D (FD DTM) – 3D Strings used to form FGL TIN of a Carriageway surface model								
1_CW_3D_ConcreteSurfEdge	128	128	128		Continuous	0.50 mm	Y	FGL – Edge of Concrete feature, V-Channel, Pad, Etc
1_CW_3D_CrownOrGradeBreak	0	0	0		Continuous	0.50 mm	Y	FGL – The crown line or grade break needed to correctly model falls
1_CW_3D_EdgePave	0	0	255		Continuous	0.50 mm	Y	FGL – Edge of Tarmac (Water Line at base of kerb if present)
1_CW_3D_Intercept (DayLight)	255	0	0		Continuous	0.50 mm	Y	FGL – The point at which a slope "Daylights" to the OGL surface
1_CW_3D_KerbTopBack	255	128	128		Continuous	0.50 mm	N – Only if needed	FGL – The top and back of a kerb unit. Never used for setting out. Keeps verge gradient correct
1_CW_3D_NmuEdge (Footways)	0	208	208		Continuous	0.50 mm	Y	FGL – The edge of an NMU surface (edge of tarmac, edging kerb or unbound surfacing)
1_CW_3D_WallEdge	215	78	39		Continuous	0.50 mm	Y	FGL – An indicative 3D representation of a structural wall (top/bottom)
1_CW_3D_StructureEdge	205	98	49		Continuous	0.50 mm	Y	FGL – An indicative 3D representation of a structure (Generally the void or outline)
1_CW_3D_Verge (Top or Bottom of Bank)	0	128	0		Continuous	0.50 mm	Y	FGL – Top of bank if in Fill area, bottom of bank if in a Cut area.
1_CW_3D_VergeGradeBreak (Non SI Boundary)	255	167	79		Continuous	0.50 mm	Y	FGL – A line which effects TIN geometry in the verge but is not top or bottom on bank (landing, etc).
01 – CARRIAGEWAYS 3D (Non DTM) – 3D strings relating to roads that don't need to be included in TIN triangulation but may be useful for reference								
1_CW_3D_FenceEdge	49	98	205		Continuous	0.50 mm	N – Only if needed	A line which represents a fence line or highways boundary, not generally included in DTM

1_CW_3D_RoadMarkings	128	0	128		Continuous	0.50 mm	N – Only if needed	A line which represents a road white lining feature, not generally included in DTM
1_CW_3D_VRS (Resistant Systems)	153	153	76		Continuous	0.50 mm	N – Only if needed	A line which represents a Vehicle Restraint System (VRS), not generally included in DTM
01 – PONDS & DITCHES 3D (FD DTM) – 3D strings relating to Pond and Ditch Geometry, used in the formation of the FGL TIN surface								
1_PD_3D_DitchBottomEdge	64	128	128		Continuous	0.50 mm	Y	A Line which represents the bottom edge of a pond or ditch, both LHS and RHS
1_PD_3D_Feature (Wall or Structure)	255	0	128		Continuous	0.50 mm	Y	A Line which represents a pond or ditch feature: headwall, gabion basket, weir
1_PD_3D_GradeBreak (Non SI Boundary)	255	128	0		Continuous	0.50 mm	Y	A Line which represents a change in TIN geometry of a pond or ditch. Site Improvement are allowed to flood over this line.
1_PD_3D_Intercept	255	0	0		Continuous	0.50 mm	Y	A Line which represents a pond or ditch intercept (Daylight) line either Cut of Fill
1_PD_3D_InvertOrAlignment	255	255	255		Continuous	0.50 mm	Y	Typically, a centreline which represents a ditch invert or the original horizontal and vertical alignment from which the ditch corridor was created
1_PD_3D_Landing	206	103	0		Continuous	0.50 mm	Y	Lines which represent a pond or ditch flat landing, often a maintenance path or ecological shelf.
1_PD_3D_WaterLevel	127	255	212		Continuous	0.00 mm	N – Only if needed	Non-corridor-based modelling – A 3D line which represents mean water level
06 – SURF SLOPE (Indicators)								
6_SURF_CUT_SlopeIndicators	254	92	97		Continuous	0.30 mm	Y	Stores embankment cut slope indicator linework
6_SURF_FILL_SlopeIndicators	0	165	244		Continuous	0.30 mm	Y	Stores embankment fill slope indicator linework
6_SURF_Gradient_Text	0	0	0		Continuous	0.50 mm	Y	Stores embankment gradient text for operator reference

The design feedback loop

The design feedback loop typically consists of an engineering design company, a Tier 1 contractor and an earthworks subcontractor. The design model is created by the design company and, for the purposes of this report, consumed by the earthworks subcontractor. The design model must pass down this chain and any feedback on the model must be passed back up. This is a long-standing process, which contains many barriers, and impacts project delivery. Design for Machines is being implemented in the light of this current situation. However, as Design for Machines is seeking to increase automation and reduce human interaction, its introduction highlights these existing problems and how they confound the achievement of smooth processes to achieve design models for Machine Control. This section focusses on the impact the issues that affect the ambitions for Design for Machines.

Challenges and implications

Assumptions at the beginning of the design process

Initial design work is conducted using survey data collected early in the process. This may be before a location has been confirmed and land access obtained. This limits the accuracy to which it is possible to survey and, regardless, the site may change in the intervening period.

The early stages of construction can also change the site significantly. The depth of topsoil will have been estimated for the purpose of creating the design. This is because there is no routine method of measuring its depth across the site. Therefore, its removal will change the Original Ground Level (OGL) and where starter layers, which are built on top of it, will need to be positioned.

Therefore, there are major assumptions made about the site and, particularly the OGL, which are not possible to validate until construction has commenced. This causes differences between the design model and the site. The design model will be very precise but, in relation to these differences, it will be inaccurate.

Slow design feedback loop

Currently, when an issue with the design is found on site that requires a change to the design, there are many parties through which the request and information must go. Typically this would be the earthworks subcontractor, the Tier 1 contractor and the design firm. Then if a design change is made, it would have to pass the opposite way through this chain.

This is a time-consuming process. However, it may be called upon at short notice, in particular when there needs to be a decision on the design so that construction can continue. The cost of standstills on a site can be in the order of a million pounds a day. Therefore a change may be made prior to the feedback loop being completed. This can lead to a scenario where several changes are being fed through the design feedback loop at the same time. This causes each to be out of date in a different way. This can make it difficult to identify the single source of truth for the design.

This causes particular problems for Machine Control because Machine Control requires up to date drawings to be able to work. There is no capability, like human intuition, to account for a difference between the design and reality due to out of date drawings.

That the loop is slow also makes it impractical to consult the design firm for small changes necessary to facilitate the use of Machine Control (e.g. simplifying the number of points in lines or addressing issues at interfaces between subassemblies). This forces major rework of the design by the earthworks subcontractor, rather than likely simpler changes to the design conducted by its original creator.

In some cases, the design firm will no longer be on contract during construction, so the feedback loop will not exist.

Contractual barriers to technical communication

In some cases, representatives from the earthworks subcontractor, who will be loading the design onto the Machine Control system, will be prevented from communicating with representatives of the design firm due to contractual restrictions placed by other parties in the design feedback loop. Whilst there may be logical reasons for such barriers (e.g., to control changes, costs and accountability) they have the unintended consequence of blocking technical feedback between the creator and the consumer of the design model. This is an issue that confounds problem solving and continuous improvement to the construction process (even when Machine Control is not being implemented).

On site interpretation of the design

Historically, limited leeway was granted to the on–site engineers and operators to interpret the design drawings during setting out to enable them to construct the earthworks to fit the true nature of the site. This is necessary due to uncertainty in the true nature of the site that only becomes certain once construction has commenced, for example the unknown depth of topsoil as described in *Assumptions at the beginning of the design process*. Another example would be temporary works created during construction. The phases of construction are typically not known by the designers or modelled by them, but they can significantly change the terrain of the construction site. To reconcile issues such as these, human intuition and interpretation of the design drawings are required to make this process function successfully. More recently, the way large projects are managed and contracted has changed and this leeway has decreased. Therefore, the design model needs to match the site more closely.

When adopting Machine Control, differences between the design model and the true nature of the site become more important. There is a situation where there is a precise design, a Machine Control system which requires precise inputs, and site characteristics which are imprecise or not known. The Machine Control system may be unable to commence the task because the design and reality are different, and the system has no intuition on how to solve this difference. These scenarios include where the OGL in the design is much higher than the stripped OGL and therefore, when working on starter layers, the Machine Control system is expecting to be operating in free space above the true ground, not the lower position where it is now located.

Currently this type of scenario requires human intervention, and intuition, to solve the discrepancy. For example, they could modify the design model to account for the different OGL. Or the difficulties might encourage the Machine Control to be disabled for that task. This is therefore a current limitation of Machine Control and a barrier to further autonomy until a process to handle these cases is devised.

Contractors forced to take on design risk

Due to the delays in the feedback loop, contractual barriers, and the need for a human to interpret the design, earthworks contractors are currently put in a position where they must make changes to enable or continue construction. These changes are typically small and deliver the intention of the design. However, in making these changes the contractor takes on responsibility for the deviation from the design. Where Machine Control is being used, changes to the design model will be necessary to enable the Machine Control to function. This creates risk because earthworks subcontractors do not have the full view of the whole design. They therefore may not have the context to make the best design choice and may unintentionally cause later problems.

Quality assurance issues

Because the issues described above cause changes to the design model that are not necessarily fed back through the full design loop, there becomes a Quality Assurance (QA) challenge. Historically an engineer in charge of the site would confirm/sign off if work was suitable. They could account for the scenarios where human intuition had been applied to modify the design but keep the design intent. Now, earthworks can be surveyed to high degrees of accuracy and precision, and this can be compared to the design model to high precision. However, if the design model has not been updated to account for known regions of uncertainty where changes have been required, then what has been built and what has been measured will differ. QA checks on conformity with the design will fail. If the design model reflects all changes then this issue would not occur.

Recommendation: Greater use of tolerances in design models

Timescale: Within 2 years

There should be a wider use of tolerances in earthworks design models, particularly in regions where there are known to be assumptions about the site geometry.

Tolerances are the defined allowable variability in a position and are widely used in manufacturing of all products. Tolerances are not as widely used in earthworks except for finish surface layers (NH et al., 2017) and at interfaces with bridges (TfNSW, 2020), where the mating between structures is more critical. Using tolerances has the potential to assist with two current issues: design uncertainty and limitations in current autonomous capability of machines.

It is recommended that tolerances are more widely adopted, particularly to accommodate uncertainties (e.g. the OGL). Tolerances would be set during the design phase by the design firm. It should be their responsibility because they have the full understanding of all aspects of the design and how changes in one part may impact another. This is something that may not be immediately apparent to other parties in the process, who may only work on one aspect of design or build.

The application of tolerances would provide earthworks subcontractors with the ability to modify the design going into the Machine Control system to fit the true site geometry, providing it remained within the limits of the tolerance. Tolerances would hence negate the need to use the feedback loop when the modifications for this purpose are within the design model's stated tolerance, hence reducing the number of times the loop is invoked.

Using tolerances would have other benefits. It removes many of the cases where earthworks subcontractors are forced to take on design risk via small changes to the design, required to enable the Machine Control to work. If the change is within tolerance, then the design is not effectively changed. This also removes some of the QA issues because the tolerances should be considered within the QA checks.

The specification of tolerances would increase the initial work required by the designer. However it can be viewed as an exercise in proactive problem solving. A design that has tolerances successfully applied to it should give enough flexibility to enable, in most cases, quick problem solving on site without having to halt activities and require the feedback loop to be enacted. It has not been possible to quantify the cost saving of this approach, but generally "left shifting" problem solving reduces cost.

It is suggested that designers would need to consider both fundamental tolerances for the construction process (i.e. tolerances accounting for practical considerations that enable the project to be constructed to the required level of quality whilst allowing some flexibility on site) and also specific considerations for the use of

Machine Control. To define tolerances to support this latter objective, it may be necessary for the designer to have a better understanding of the nature/capability of the machine that is expected to be used to undertake the construction. This capability could potentially be communicated through the inclusion of technical capability specifications within design software.

From the viewpoint of the machine itself, current Machine Control systems require precise inputs and do not accommodate uncertainty. Although tolerances would allow rapid "adjustment" on site, the current situation with Machine Control would still require the true nature of the site to be synchronised with the design model (hence the adjustment is still a human activity). The use of tolerances could provide a basis on which CAP could be programmed to adapt and react to real world differences, within controlled limits. For example, a slope could be extended to reach the OGL prioritising a key dimension, such as the angle, within tolerances set by the other dimensions. The tolerances set by the other dimensions would ensure what was constructed remained within the engineering requirements. There is potential for this intuitive interpretation of the tolerances to be done by the machine itself. This would allow future Machine Control systems and CAP to operate with less need for human intervention, interpretation and initiative.

Recommendation: Digital rehearsal

Timescale: Within 1 year

Selected sections of the design model should be used to test all systems through which the design files will pass (between the design software and Machine Control). Representatives of all parties involved in this chain should participate (designer, contractor, subcontractor and operator). Feedback should be sought on any issues with the data transfer process and how these will be addressed in the final design model.

The aims behind this recommendation are:

- To remove as many issues as possible with the data transfer process prior to the creation of the full design model. This is to minimise rework and get things right first time.
- To provide a forum for communication to enable continuous improvement and familiarity if later problem solving is required. The stakeholder consultation found that the design and construction communities do not have a good understanding of each other's processes and challenges. The digital rehearsal will establish understanding and relationships. This should develop into a robust end to end testing process based upon a common understanding of the Design for Machines data transfer process.

Test runs should identify any software or file issues, checking that the correct information is successfully passed through the chain. This includes layer names, layer structure and layer colours. The usability of the model by operators should also be evaluated. Where software regenerates parts of the model, for example triangulation, these outputs should be checked for consistency with the design intent.

This digital rehearsal is an exercise in proactive problem solving. It should catch challenges in the data transfer process and with the design or Machine Control setup before they are embedded in the whole design model or data transfer process. This initial effort should save time and cost later in the process. Quantifying the cost reduction has not been attempted, but generally "left-shifting" problem solving reduces costs and this is particularly relevant if the issues can be prevented from reaching site.

Machine Control emulators, which are provided by all major Machine Control system providers, should be used as part of the digital rehearsal. Designers can use these to identify the issues that are likely to occur when transferring their designs to the Machine Control system. However, it is important not to use Machine Control emulators to shortcut the full digital rehearsal. This is to ensure the needs of other parties involved in the chain are considered. To aid this process, Machine Control suppliers should consider the needs of designers in future development of their emulators.

Digital rehearsals have been used successfully by Skanksa to improve their processes, as described in the following case study.

Case study: Skanksa digital fire drill

To test the suitability of design models for use in Machine Control, Skanska conduct a "digital fire drill" to test the transfer of a section of the design model to the Machine Control system. This rehearsal involves everybody who is expected to be involved in the process when it is (ultimately) carried out with the complete model on site. This includes the designer, the design manager, the information manager, and engineering surveyors or 3DMC engineers.

The digital fire drill tests the transfer of the linework and surfaces through the whole data transfer chain. This tests the design data itself and other key components that influence the data transfer process, such as the communication of the data and access to the data. The process will identify any barriers or needs for intervention in the data transfer chain.

Examples of issues the digital fire drill identifies include:

- Problems with the file formats and file sizes
- Elements missing from the model
- Incorrect layers
- Non-continuous lines
- Poor naming of model elements
- Missing explanatory information such as cross sections
- Items not in 3D or contours instead of surfaces
- Adjacent models overlapping or not joining
- Incorrect grid projections
- Inconsistent colours of model elements
- Incorrect units

By identifying these issues, the digital fire drill ensures a complete design and high-quality model is delivered which is interoperable with all systems including Machine Control. It brings further benefit because it reduces engineering costs by removing the need to "flip" or remake the model. It also reduces technical queries about the model. Due to the nature of the construction industry, it cannot construct prototypes. However, the digital fire drill enables this part of the process to be practised and improved before construction commences.

Recommendation: Single shared digital model

Timescale: Within 10 years

A single digital design model should be shared with all parties involved in the construction. This should be the single source of truth for the design. All parties should be able to update the digital model and it should be kept up to date as the site changes.

Even with efforts to improve it and speed it up, the design feedback loop will never be as reactive as desired due to the number of parties involved and the need to transfer data through different systems. Therefore, it would be more efficient to have one version of the model which is the repository for all design information for the project. The design model could act as a forum between all parties involved in the construction.

Version control of the model will need to be managed, but if all changes live in one repository, then it will be simpler to share the impact of a change and keep everyone up to date, even if a change were just kept as pending. Visibility of upcoming changes would also encourage them to be addressed, hopefully making the system reactive to changes.

By continually keeping the model up to date, it would form the basis of an accurate as-built model which could be passed to the asset owner for future asset management purposes, and would support longer term goals to achieve higher levels of BIM compliance. This would also provide a vehicle to connect construction process data to asset condition data. This could enable a greater understanding of how the construction process influences asset performance and life. For example, compaction maps could be compared to pothole locations to understand if there was a link and if compaction needed to be improved for future projects. This could inform a continuous improvement process.

If the one single model was embraced by all parties, this would remove the duplication of work which often occurs when the earthworks contractor remodels sections to incorporate site changes or to enable Machine Control to function. The shared model could act as a forum for those who created the model to learn the changes required for Machine Control.

The single model should include data from teams early to the site, such as archaeology and fencing teams. The information they gather can go some way to reduce uncertainty about the ground structure. This can be used to update the model before earthworks begin, ensuring the models are the most suitable they can be for the precise inputs required by Machine Control.

A properly controlled and up to date digital model will remove one of the issues around QA. Updates to the model will have accounted for real world differences. Therefore, if the finished earthworks match the model, they can be confirmed to have passed the QA checks. It does however add a requirement that changes to the model need to be verified. This is to ensure changes have not adversely affected the desired engineering outcome, or interfere with other parts of the design or the plan for construction. Hence there will be an additional responsibility to approve changes in the design in tandem with ensuring quality is unaffected.

To enable working with a single digital model will require significant changes to current working practices. The body responsible for the single digital model will need to be identified and the model management (build, maintain, collaborate, deliver) included in the procurement of the construction (if the model is to be the responsibility of a 3rd party). All parties will need to be trained to use, share and collaborate on the single model. This will be a significant initial burden to overcome, though, as it becomes the normal way of doing construction, that burden will decrease due to industry experience.

The single digital model would also require the modelling of each phase of construction. This is to keep the model up to date with things such as the true OGL, subgrade, and temporary works. Currently these phases are typically not included in the design model. This is known as 4D design, which is a 3D model which also includes changes over time. This would require additional work but would also proactively address many of the current issues, both when using Machine Control and otherwise, caused by discrepancies between the model and reality.

The use of a single digital model has been successfully pioneered by the Norwegian Road Public Roads Administration, as discussed in the following case study.

Case study: BIM adoption in Norway

Norway has become a world leader in digital construction. For highways, this has been achieved by requirements from clients, and simultaneously design and construction companies embracing BIM technology. The Norwegian Road Public Roads Administration (Statens vegvesen – SVV) created Handbook V770 in 2012, since updated (SVV, 2015), which states detailed requirements for modelling throughout the construction process and the roles and responsibilities in this way of working. The handbook includes:

- That there is a single digital model which is shared between every party involved in the project.
- The deliverables for design and survey data are 3D digital models.
- The model has phases covering all parts of the construction process including concept, tendering, construction and as built. The construction phases will also be modelled.
- The model can be updated by the different parties involved in construction, including during the construction phase. There are requirements for what forms of data are accepted to do these updates to ensure the quality of the model is maintained. There is a defined procedure and set responsibilities for this process.
- File types (SOSI or LandXML) and survey tolerances are set to ensure interoperability and model quality.
- The expected roles and responsibilities for storing, managing and updating the digital model are defined. The client organisation typically hosts the model.
- Any drawings delivered separately to the model must be derived from model data and show it unchanged. This is to minimise discrepancies between the model and drawings which can cause errors or confusion.

Contracts for new highway construction have required the supply chain to adopt this method of working partially or fully. In some cases the requirements to adopt a digital model have come from the construction contractors themselves (Naborczyk, 2020a). Many roads are constructed using design and build or private public partnership contracts which, in terms of digital construction, have the advantage of enabling a close working relationship between the design team and the construction team. This reduces many of the barriers and the time required to change the design model. It also enables design and construction activities to occur simultaneously, with information from the construction site being used to improve the design (Novapoint, 2019).

Norway's adoption of BIM technology is also highlighted by the widespread adoption of related training courses and certification. Many companies have sent staff on Virtual Design and Construction courses at Stanford University, and the Norwegian University of Science and Technology (Naborczyk, 2020b).

Conclusions and summary recommendations

The National Highways roadmap for Connected and Autonomous Plant (CAP) identified a need for the design of highway construction to adapt, with the consumer of the design now potentially being an automated system (Machine Control) instead of a human. The current processes to transfer the necessary information for construction from the design model to the Machine Control system require improvement, to achieve the objective of "Design for Machines".

The stakeholder engagement undertaken in this work has shown that the current design process for highway construction does not accommodate the technical requirements of automated systems such as Machine Control. This is a barrier to the use of Machine Control and adoption of CAP. In particular:

- The requirements for labelling and naming design models are complicated and inconsistent, making them difficult to interpret and manage in a Machine Control system.
- The design models are large and complex, often containing more information or detail than is required by the Machine Control system for the particular component of construction currently taking place.
- The processes to extract the information from a design model to feed into a Machine Control system are lengthy, require technical skill and, often, major rework of the model.

It is recommended that **there should be a national specification, incorporated into GG 184, for models intended for the production of earthworks using Machine Control.** This will enable automation of the data transfer process and ensure the design displayed in the Machine Control device is accessible to the operator. The set of layers and the naming and colour scheme should become a deliverable from the design process. It can then be checked against the requirements for quality by the designer. Aspects that would need to be checked would include interface continuity, minimised node count, removal of unnecessary layers, and conformance to the colour and naming scheme. These would improve the efficient transition from the design to the Machine Control system with reduced human intervention. This work has identified a good practice example implemented by MJ Church that could be used as a template for this specification.

The work has also identified several challenges in the wider design and construction feedback loop. In the initial design there are uncertainties in the design model, which are caused by assumptions about the site which cannot be confirmed until construction commences. However, updating the design model during construction is a slow process due to the number of parties involved. This impacts the use of Machine Control because the inputs to the Machine Control system come from the design model and Machine Control systems do not have the capability to independently handle large deviations between the model and reality. Therefore, there is a need to keep the design model up to date. To achieve this, the design feedback loop needs to operate more efficiently. In the light of this the work makes three recommendations.

There should be a wider use of tolerances in earthworks design models. This will empower earthworks contractors to make moderate changes to the design within a controlled structure, with confidence that these changes will not impact the desired engineering outcome. This would minimise the need to invoke the design feedback loop.

A digital rehearsal should be undertaken, using selected sections of the design model to test all systems through which design files will pass (from the design software to Machine Control). All stakeholders in the chain should participate. This should be undertaken before the work on the design model is complete. This will enable issues in the process or with the model to be identified and addressed proactively. It will also provide an opportunity to build a good working relationship between the parties involved to ease later problem solving.

A single digital design model should be shared with all parties involved in the construction. This should be the single source of truth for the design. Achieving the long-term goal of a single shared digital model would provide an accurate as-built model that can be passed to the asset owner for future asset management purposes, supporting longer term goals such as application in asset management and higher levels of BIM compliance. During construction the model will facilitate collaboration and sharing of the design, superseding the design feedback loop, ensuring the design is always up to date, and simplifying inputs to Machine Control and other future CAP systems. Although the adoption of a single shared digital model will require major changes to the current way of working, and new roles and responsibilities, it has the potential to simplify the currently disjointed process.

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Appendix A Methodology

To understand the barriers and challenges faced by industry when using machine control, a series of workshops were organised with participants from all parts of the CAP ecosystem. The first workshop focused on identifying challenges with the Design for Machines process and understanding what to prioritise. The second workshop gathered best practice and solutions to the challenges and barriers were discussed. Finally, part of the demonstration day aimed to share the best practice and gather feedback on it. Throughout the series, further discussions were held with individuals or small groups where their expertise and knowledge benefited the findings of the project.

Workshop 1

The workshop on 6th June 2023 aimed understand the key challenges around Design for Machines faced by National Highways' supply chain. The purpose of the workshop was to bring together representatives from all stages of Design for Machines who could share their current experience on problems and seek consensus on the biggest challenges. The workshop was conducted online.

32 participants were split over 6 break-out groups. These break-out groups were selected so that a mixture of designers, construction contractors, software and Tier 1 organisations were included in each group. All groups were facilitated by a member of the project team.

The workshop was split into stages. During each stage participants were asked to add online post-it notes to a board before feeding back what they had suggested to their own group. The facilitator of each group would then fed-back the most important points raised in a whole group discussion.

In the first stage, participants were asked to identify the problems with achieving Design for Machines. In the second stage, participants were asked which of these suggested Design for Machines problems were the most critical, and to comment on which should be prioritised. Finally, participants voted on which of the problems were the most important to them in their role.

Overview

Objectives

1. Validate a basic process from designing and software through to surveying and construction.
2. Identify and consolidate all the challenges and barriers to achieving Design for Machines.
3. Discuss how to prioritise to deliver the most impact.

Attendees

Attendees included representatives from:

- Engineering design companies
- Design software developers
- Tier 1 contractors
- Tier 2 contractors
- Machine Control system developers
- Plant hire companies

Format

Location: Virtual
Duration: 2 hours
During the workshop, attendees were able to provide input using Miro, a virtual whiteboard. Additionally, attendees were split into breakout rooms for discussion. Each breakout room was led by a TRL facilitator and featured a mixture of attendees from different parts of the National Highways supply chain.

Agenda

- Task 1: What are the challenges and impact you see in achieving Design for Machines?
- Task 2: How do we prioritise going forwards?
- Task 3: Voting on the challenges most worth actioning (based on the impact and effort).

Key challenges

These four key challenges were identified by the workshop:

Contracting
Challenges surrounding how contracting is carried out and the contents of those contracts. Examples:

- There is no specification for Design for Machines.
- The design community do not have Design for Machines requirements in their contracts.
- The majority of design contracts still focus on 2D deliverables over 3D outputs.

Lack of feedback loop
Challenges stemming from the lack of feedback between the different parties in the supply chain. Examples:

- There is no sharing of feedback between the different members of the supply chain.
- There is a waterfall cross over from the design phase to the construction phase.
- Construction teams are not usually involved during the design.

Complexity of design models
Challenges faced as a result of design models being too complex for Machine Control systems. Examples:

- Design models contain too much information and unnecessary layers for Machine Control systems.
- Often, the profiles in design models are far too complicated compared with what can be built in reality.
- There are often too many points and polylines in the design models for use by Machine Control systems.

Unknown requirements for Machine Control
Challenges faced due to the inconsistent requirements of Machine Control systems and the lack of clarity for designers. Examples:

- There is no prescribed set of requirements from the construction organisations to the designers for Design for Machines.
- There is no common data format across different machine control systems.
- Variable formats result in the need for differing routes to ‘flip’ designs to prepare them for the machine control systems.

Workshop 2

Workshop 2 was an in-person event, on 5th October 2023, that aimed to understand which solutions could be developed to overcome the barriers identified in the first workshop. 19 participants were present, from a range of earthworks, technology, design, Tier 1 and surveyor organisations. The day began with an introduction to the outputs of the previous workshop, and an overview of Design for Machines. Following this, a discussion began regarding the present problems with Design for Machines. Participants were then asked to suggest potential solutions for the challenges facing Design for Machines and these were discussed in detail. Opportunity was given to all parties in the ecosystem to discuss the impact of potential solutions on other parties. Throughout the day potential solutions were recorded on post-it notes. Towards the end of the workshop the group sorted these into one of four categories: contractual, human, organisational and technical.

Overview

Objectives

1. Understand what needs to be done to overcome the challenges facing Design for Machines.
2. Understand how these changes can be implemented.

Attendees

Attendees included representatives from:

- National Highways
- Engineering design companies
- Tier 1 contractors
- Tier 2 contractors
- Machine Control system developers
- Plant hire companies

Format

Location: Harper Adams University
Duration: 1 Day
The workshop consisted of round table group discussions on the major challenges identified during workshop 1. These were led by a TRL facilitator. The day also included sessions of recording ideas from everyone on post–it notes so all present could make and read others suggestions.

Agenda

- Presentations on Design for Machines from a design and construction perspective.
- Task 1: Round table recap on the challenges facing Design for Machines.
- Task 2: Round table suggestions of solutions to the challenges.
- Task 3: Categorisation of the solutions into contractual, human, organisational and technical factors.

Key findings

The key findings from the workshop have informed the main contents of this report. The main themes of the solutions identified were:

Communicating the needs of Machine Control to designers

- The needs of Machine Control need to be communicated to the design community so they can deliver design models that can accommodate them.
- The core needs of earthworks subcontractor should be defined as a data specification for Machine Control. This data specification should consider the needs of the operators on site.
- Other issues with the suitability of design models for Machine Control, such as issues at interfaces, unsuitable triangulation or too many points, should be fed back via better industry communication.

Responsibility for design changes

Earthworks contractors currently have to make major changes to the design models to prepare them for setting out and Machine Control use. Implications:

- There is the risk that the design is changed in this process. Where this occurs, the contractor takes on design responsibility for this change.
- The changes have an impact on the quality assurance process.
- The extent of the contractor's authority to make changes needs to be clarified.

Feedback loop

The feedback loop between designers and earthworks subcontractors is too slow and not well accommodated in contracts. There were a wide range of solutions proposed on this theme which informed the recommendations in *The design feedback loop*.

Ecosystem wide communication

- Communication needs to be improved between the design community and the earthworks community so that best practice and mutual understanding of challenges can be shared.
- Design for Machines requirements need to be communicated to design software providers so the technical aspects of these processes can be improved.

Demonstration day

The final part of the series of events was a day to demonstrate the challenges with the current Design for Machines process and show how some of the recommendations could improve the process. The event was held at the Operator Skills Hub on 14th December 2023.

During the demonstration day, the opportunity was used to gather further opinions on the challenges with the Design for Machines process and how best to address them. In particular, the proposed layer naming and colour scheme was discussed amongst the 30 participants. Feedback from representatives of engineering design firms suggested providing this as a deliverable was highly feasible and there were several technical methods to achieve it. One issue that may remain until technical solutions can be developed is how to keep the earthworks specific outputs in synchronisation with the rest of the design model, should either change.

Overview

Objectives

1. Show how the various issues with current design models manifest themselves in Machine Control.
2. Share a basic understanding of Machine Control with the whole CAP community.
3. Gather feedback on solutions, particularly the proposed layer names and colour scheme.
4. Continue community engagement to share best practice and create opportunities to build relationships.

Attendees

Attendees included representatives from:

- National Highways
- Engineering design companies
- Design software developers
- Tier 1 contractors
- Tier 2 contractors
- Machine Control system developers
- Plant hire companies

There was a focus on attracting attendees from engineering design companies to widen their exposure to the needs for Design for Machines.

Format

Location: Operator Skills Hub
Duration: 1 day
Predominantly group activities with opportunities to explore parts of the Design for Machines process or to gain familiarity with Machine Control devices.

Agenda

- A presentation introducing common issues with Design for Machines and the need to prioritise operator accessibility.
- Group activity 1: Exploring the proposed layer naming and colour scheme.
- Group activity 2: Discussing Machine Control capability and needs with Machine Control system developers.
- Group activity 3: Experiencing 3DMC in an excavator simulator.
- Group activity 4: Discussing issues with examples of design models when loaded onto Machine Control without preparatory work.

Appendix B Stakeholder acknowledgements

This report and the recommendations have been created drawing on the expertise and knowledge of stakeholders from the following organisations.

AECOM

Amey

Arcadis

Arup

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Autodesk

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Costain

COWI

Ferrovial

Finning

Flannery Plant Hire

Gattica Associates

GRAHAM

Harper Adams University

Jacobs

Kier

Leica Geosystems, part of Hexagon

L Lynch Plant Hire & Haulage

M O'Brien Plant Hire

Mick George Group

MJ Church

MKL

Mott MacDonald

National Highways

Ramboll

Severn Partnership

SITECH UK

Skanska

Topcon

Trimble

TRL

Walters

WSP

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