

Supplemental Material 3 - Thematic coding examples

Topic	Theme	Code	Focus Group				Verbatim quote example 1	Focus Group				Verbatim quote example 2
			1	2	3	4		1	2	3	4	
Evaluation KPIs	Usefulness and Insight	Addresses domain needs				4.3	"I can see this being directly useful for the things we want to do in government. Having a software architecture written out for the ICMS3, we would love to be at that stage."	2.3				"This would be very beneficial for FMs. Perhaps less useful for QSs, but really interesting for REITs for managing their assets. I think you've got an incredible opportunity to commercialise this."
		Supports decision-making				3.2	"You're still trying to predict the TCO, that doesn't change. 'Am I hitting my target?' Then you can make decisions. 'Do I sweat, do I bring through, refurbish rather than replace?'"				4.1	"If I knew CAPEX was going up because I've done something for carbon, but could show the OPEX was going down, then I've got real value for money. I know I've paid more to get a better deal over the lifespan."
		Provides transparency and visualisation	1.6				"I already know some people who would be really excited about what you've shown us today, at least within our organisation, a lot of need for this sort of communication, especially reliability engineers looking ahead."	1.2				"Standardising the data layer, as you've done, will demonstrate quality of the final results."
		Formalises domain knowledge	1.1				"The data model is important, substantial scope in any system building is doing the domain modelling. Saves a lot of time adopting existing rather than building your own with scalability benefits."	1.1				"The sequence diagrams and plain language code are very useful, but more specific user requirements will always be needed to lead to an implementation. [...] Simple description of typical requirements, usually needs to be gathered from the user. It's the first thing that the software developer will ask you and good to include here."
	Flexibility and Ease of Use	Supports various stakeholder objectives				2.3	"This would be very beneficial for FMs. Perhaps less useful for QSs, but really interesting for REITs for managing their assets. I think you've got an incredible opportunity to commercialise this."				3.2	"This analysis would fit government style, local authority without much alteration, as they will try to match their prediction with spend. [...] But also REITs who want to see the profitability of their investments, but at a different granularity."
		Adaptable to case-specific nature of domain				3.1	"Adjust parameters and see the results immediately. Really useful for simulating. I think it's brilliant. In this model you can play with the money etcetera, but also with the study period length, I think it's beautiful! You see the TCO for one or multiple. I think what you've done is very flexible and with small adjustments can be widely useful."	2.3				"For me the key is flexibility. You're not going to have all costs in every life cycle costing exercise. Every case is different than the one before."
		Easy to use				2.1	"I'm blown away to be honest with you, I think it's unbelievable. Just type it in and it just comes out in a graph. I think you've got something big time here."	2.3				"I've been doing it in spreadsheets for years. It's laborious, using macros and pivot tables [...] I eventually found someone who could write me an advanced formula [...] I can maybe do some of the stuff you're outputting but it's tedious and time consuming."
		Automates complex calculations				2.3	"It's typical just to accept inaccuracy because of that complexity. I eventually found someone who could write me an advanced formula, but for the lay-person, they're not going to have the know-how to go back through 75 years of analysis and start deleting out renovation values where they overlap with replacements. So it's brilliant that it does this."				3.1	"When you have the calculation model in a programming language and can connect to different databases it becomes very powerful."
		Provides guidance for implementation	1.1				"The sequence diagrams and plain language code are very useful, but more specific user requirements will always be needed to lead to an implementation. [...] Simple description of typical requirements, usually needs to be gathered from the user. It's the first thing that the software developer will ask you and good to include here."	1.4				"The very generic is a good starting point, but that's never where it's going to end up. It's going to end up specific because of the real scenario constraints. So try to tease out reusable design patterns."
	Representativeness and Scalability	Useful for different stakeholders				3.2	"This analysis would fit government style, local authority without much alteration, as they will try to match their prediction with spend. [...] But also REITs who want to see the profitability of their investments, but at a different granularity."	2.3				"This would be very beneficial for FMs. Perhaps less useful for QSs, but really interesting for REITs for managing their assets. I think you've got an incredible opportunity to commercialise this."
		Representative of wider domain				2.3	"This would be very beneficial for FMs. Perhaps less useful for QSs, but really interesting for REITs for managing their assets. I think you've got an incredible opportunity to commercialise this."				3.1	"Adjust parameters and see the results immediately. Really useful for simulating. I think it's brilliant. In this model you can play with the money etcetera, but also with the study period length, I think it's beautiful! You see the TCO for one or multiple. I think what you've done is very flexible and with small adjustments can be widely useful."
		Potential for scalability				4.1	"I can see this being directly useful for the things we want to do in government. Having a software architecture written out for ICMS3, we would love to be at that stage. Keep us (gov.) in mind with what you're doing, might align with our plans."	1.4				"Standardising the data model. That's where you have scale benefits. The question is 'how opinionated you want to be in reference architecture?' The more opinionated you are, the tighter you design your spec, and the easier and clearer it'll be for software developers to implement, but the more constrained in use cases and customers you can support. There's a continuum. Very formal, or very flexible."
Domain Insight	Sectoral Requirements	Support different strategic goals				3.1	"The goal of this case study is to 'reduce TCO' but if you take another goal, for example, 'run at minimum and invest at end of conveyance to handover at agreed condition', how to imagine that kind of goal-setting in the software?"	2.3				"The challenge is trying to get a tool that is applicable to a number of different exercises, buildings, scopes, stages of lifecycle and detail of estimates."
		Flexibility per case				2.3	"For me the key is flexibility. You're not going to have all costs in every life cycle costing exercise. Every case is different than the one before."				3.2	"This analysis would fit government style, local authority without much alteration, as they will try to match their prediction with spend. [...] But also REITs who want to see the profitability of their investments, but at a different granularity."
		Data exploration (data-drilling, filtering)				3.1	"In asset management we try to look into assets which are not obvious, we need the flexibility to filter and query the data in very specific ways."	1.4				"Grouping data by some grouping method will be needed. 'Let's upgrade all X'. Could be 'type', 'make' or 'condition'. This is how larger companies tend to operate. Portfolio-level refresh."
		Simulate and measure				3.2	"This is a fixed cost prediction. Can you look at what it really cost? What you think it should be versus what it really cost to see where you're going with your prediction. Can you show that?"				4.1	"Need an evidence-based approach to decision-making in public projects."
		Optimise resources				4.3	"It's about integration, getting best from systems in place. Particularly with existing stock we need to optimise what's there."	2.2				"O&M is going to come under a lot more scrutiny, especially in public buildings, including disposal. Decisions need to be evidence-based."
		Public cost database				4.1	"Even in central government there is no dataset of any of those values outside of maybe a project group, let alone in a department. That's a major failing. People are just emailing each other spreadsheets of this incredibly valuable data."	2.3				"Government procurement want some sort of public database of costs which QSs and others can refer to."
	Trajectory of sector	Focus on lifecycle				2.2	"O&M is going to come under a lot more scrutiny, especially in public buildings, including disposal. Decisions need to be evidence-based."				3.2	"Investors want the long-term view, but are informed of viability by the short-term, more granular asset management view."
		Performance-based contracts				3.2	"You're looking at a long time here. A lot is going to change outside of your control, so for this to work you need to be able to adjust that baseline, set checkpoints to see where you're going with your prediction, otherwise you can't compare. And the contracts need to facilitate this."	2.1				"Capital Works Management Framework is changing how we do public sector work. Consultants can no longer get away with providing just construction costs, will need operations too. [...] If we're not hitting the targets we're hit with deductions."
		Sustainability driver				4.1	"Climate has changed where we can go, has removed barriers that were previously there. We've been able to utilise the climate issue to push on with so many things. We need to make sure that tools like your own come in to play, to show efficiencies and inefficiencies of thought."	2.1				"Capital Works Management Framework is changing how we do public sector work. Consultants can no longer get away with providing just construction costs, will need operations too. [...] Green procurement is also becoming important. We need to show that we're making sustainable decision."
		Requirement for evidence-based decision-making				3.2	"Need to know how much we'll be spending in future so I can give assurances to those looking at profitability. If you don't have this you risk shock-waves, and no business wants shock-waves."	2.2				"O&M is going to come under a lot more scrutiny, especially in public buildings, including disposal. Decisions need to be evidence-based."
		Standardised methods				4.1	"The International Cost Management Standard, Version 3 is coming in January 2024. It replaces the old QS cost centres and allows for consistency in reporting, across state portfolio and internationally, on CapEx, OpEx and carbon."	1.4				"Standardising software components to ingest data from other sources to build a database in a way that makes sense. That's where you get scale."
	Domain Insight	Data access and availability				4.2	"LCC for us is based around not just MEP but the structure itself. Structure doesn't have those same metered values."				4.3	"The technical systems within the same building are siloed and not interacting with each other, no interoperability. Equally, there are the organisational silos. HR, facilities, operations... they're not talking to each other and are protecting their data, not giving others even within the same organisation access."
		Data quality				2.3	"The data quality was so bad that I went back to my spreadsheets, at least then I know what's going in there."	1.6				"Need a common structure for external data. We're running into this. Lots of distributed data and different applications, and all departments claiming data quality."
		Performance gap				2.1	"It's hard enough to try to estimate construction costs, never mind O&M costs over a 25 year conveyance period. Trying to keep to an annual budget is impossible."	2.3				"No matter how good your model is, no-one could have predicted how inflation and energy prices would have gone in the last few years."
		Rate of technological change (like-for-like challenge)				2.2	"No one could have predicted the technological progress in photovoltaics we've seen. So how to make those estimates and validate them? How technology changes in 5 years, or even 6 months. You're not replacing like-for-like. Can't even get like-for-like!"				3.1	"Technological change is always an issue when comparing assets for renewal or revival, it's just part of the business. It's difficult to factor that in over building lifetimes."
		Difficulty in predicting future				2.3	"No matter how good your model is, no-one could have predicted how inflation and energy prices would have gone in the last few years."	2.1				"There's a difficulty in trying to predict the future and then being held accountable for that in PPPs. Needs a more nuanced approach to administering the contracts. Otherwise contractors are afraid to lose their shirts and will be over costing. Needs a pragmatic approach, maybe five year reviews."

Recommendations and Future Work	Sectoral challenges	Lack of available life cycle costing systems			4.3	"I've been in the game 15 years and haven't come across anything commercially available that does this type of analysis. I'd say it's because it's difficult. More difficult than extracting data from a building, and that's difficult. I mean you're looking at asset registers. I don't think I've come across a decent asset register."	2.3		"If there was a tool that can be used by someone without my background, that would make it easier. LCC has been around for decades, but I never used it in industry because there just was no software like there was for QS: Cupid, CostX etc. There was nothing to make it easier for me."
		Manual effort in current analysis methods	2.3			"I've been doing it in spreadsheets for years. It's laborious, using macros and pivot tables [...] I eventually found someone who could write me an advanced formula [...] I can maybe do some of the stuff you're outputting but it's tedious and time consuming."		4.3	"I'm currently dealing with well known company. They're manually collecting metre data, putting that into a spreadsheet for global reporting, extracting from that first spreadsheet and putting it into another one to do their LCC."
		Variation in asset management goals between sectors (buildings/infra, public/private)		3.1		"That's true for hotels and apartments, but when we're talking about public money, hospitals, infrastructure, they don't really use that sort of investment strategy. There's a difference between public and private real estate investment strategies."		4.1	"There's a different mindset about what the state build. We hand over to another state agency so it's still part of our spend. We're not a developer. We haven't sold it, we're retaining it."
		Goals vary between stakeholders	2.2			"Great for finance department, they get a balanced cashflow, but then you're pulling forward cost and you need a really good validation for that. Maybe you're doing lighter maintenance more frequently rather than a big cost later. Don't get me wrong, it's good to smooth cashflow, but you have to have a really good justification. Need to give something back."	3.1		"That's true for hotels and apartments, but when we're talking about public money, hospitals, infrastructure, they don't really use that sort of investment strategy. There's a difference between public and private real estate investment strategies."
		Accounting for risk	2.1			"There's a difficulty in trying to predict the future and then being held accountable for that in PPPs. Needs a more nuanced approach to administering the contracts. Otherwise contractors are afraid to lose their shirts and will be over costing. Needs a pragmatic approach, maybe five year reviews."	3.2		"You're looking at a long time here. A lot is going to change outside of your control, so for this to work you need to be able to adjust that baseline."
		Systemic sectoral issues (contractual)			4.3	"Need a design-thinking approach, early designer involvement including the operational team. I'm only familiar with the private sector, but there it doesn't happen at all."		4.1	"We're moving away from a 'most economically advantageous tender (MEAT)' model. This has been the industry norm and quality is always left out."
		Stakeholder relationships	2.1			"They're getting better results from their public-private partnerships that are coming to term. Closer to predictions than in this country [...] It's a lot about relationships, depends on a good funder who will work with you, and ultimately it's an ongoing negotiation. We can't stick rigidly to agreements on how the asset is used, that sours relationships. It's a grey area."		4.3	"The technical systems within the same building are siloed and not interacting with each other, no interoperability. Equally, there are the organisational silos. HR, facilities, operations... they're not talking to each other and are protecting their data, not giving others even within the same organisation access."
		Lack of buy-in			4.3	"Have had endless discussions with manufacturers. They're still sticking their heels in, saying 'We're not going by your data-driven maintenance management. We're going to continue with our 100 year old PPM policies.'"		4.1	"We have to lead from the top-down and provide guidance. Right now, contractors are expected to do an LCC with material that was designed by someone else in generic terms."
	Recommendations to improve the research	Define research scope and limitations	1.5			"For the 'Lifetime', are you taking the manufacturer's values? Is it fixed? Are you taking any historical experience into the model?"	1.3		"It's a bit vague what's included in the recommendations. Are systems interconnected? Make it clear what is the research scope."
		Improve communication of research		3.1		"Needs to be clear to user why are costs getting lower over the years? Important to note in the display that it's depreciation."	2.3		"I'm a little confused about 'study period' and 'lifetime'. Can you clarify these?"
		Extend functionality			4.1	"It's missing the carbon piece. To date there has been more focus on carbon in use and we haven't even scratched the surface on embodied carbon."		3.2	"Public contracts are totally different. You need to try to build it into the system. At the start you need a 'public or private' button."
		Automate data-entry	1.2			"Motivate the user by reducing manual inputs. Connect to external sources."		4.3	"Getting data out of buildings is the easy part. I'd like to see your system integrated with databases which are feeding real data and evidence-driven maintenance plans through integration and optimisation of systems."
		Improve prediction			3.1	"I don't think corrective maintenance is in your model. The system should perhaps look at the 'warranty', 'condition' and 'age' metrics to estimate corrective maintenance based on historical data."		3.1	"Everything to the right of the red line is a prediction, still uncertain. The prediction can get better if we take in real data."
		Improve user experience	1.2			"Motivate the user by reducing manual inputs. Connect to external sources."	2.3		"Could you turn it into a web-based tool and give is an easier graphical interface?"
		Sanity-check model		2.2		"Practitioner will want to sanity-check the model. Make sure they can run analysis on an asset they know and you'll build confidence in the analysis."		3.2	"I'd like to see simulation of real completed cases, take something tangible where we know what the outcomes were. Could see where things were astray and compare with real events."
		Incorporate broader goals			3.1	"The goal of this case study is to 'reduce TCO' but if you take another goal, for example, 'run at minimum and invest at end of conveyance to handover at agreed condition', how to imagine that kind of goal-setting in the software?"		3.2	"Public contracts are totally different. You need to try to build it into the system. At the start you need a 'public or private' button."
		Improve the reference architecture	1.1			"Simple description of typical requirements, usually needs to be gathered from the user. It's the first thing that the software developer will ask you and good to include in the reference architecture."	1.1		"The data model is important, substantial scope in any system building is doing the domain modelling. Saves a lot of time adopting existing rather than building your own with scalability benefits."
		Establish strategic partnerships	1.4			"It won't be picked up sufficiently by regular publication routes, need to form strategic partnerships with stakeholders who can showcase the work."		4.1	"I can see this being directly useful for the things we want to do in government. Having a software architecture written out for ICMS3, we would love to be at that stage. Keep us (gov.) in mind with what you're doing, might align with our plans."
	Directions for future work	Accessibility (web-based portal)			4.1	"There should be a web-based portal so that it's accessible by suppliers."	2.3		"Could you turn it into a web-based tool and give is an easier graphical interface?"
		Distributed data integration	1.4			"Standardising software components to ingest data from other sources to build a database in a way that makes sense. That's where you get scale."		4.3	"There are multiple datasets across systems in a building, across the portfolio. Allowing teams within the organisation to get access to the data makes it much more 'meaningful' and you'd then be able to do all that lifecycle costing and crystal ball gazing."
		Predictive maintenance			4.3	"There's a missed opportunity around using available software to go from planned preventative maintenance-type models into predictive and prescriptive. Then you're really managing the asset from the life cycle perspective so that we're not sweating anymore. There's no need for sweating!"		4.2	"There's huge potential with predictive maintenance for the state as an asset manager."
		Data exploration			3.1	"In asset management we try to look into assets which are not obvious, we need the flexibility to filter and query the data in very specific ways."		4.2	"Would it be expandable for use with AI in future? What about using language models to query the data?"
		Further case studies			3.2	"In order to demonstrate viability and build confidence, take some public data and carry out further testing."		3.2	"I'd like to see simulation of real completed cases, take something tangible where we know what the outcomes were. Could see where things were astray and compare with real events."
		Commercialisation	2.3			"This would be very beneficial for FMs. Perhaps less useful for QSs, but really interesting for REITs for managing their assets. I think you've got an incredible opportunity to commercialise this."	1.6		"I already know some people who would be really excited about what you've shown us today, at least within our organisation, a lot of need for this sort of communication, especially reliability engineers looking ahead."
		Nuanced approach to performance-based contracts			3.2	"You're looking at a long time here. A lot is going to change outside of your control, so for this to work you need to be able to adjust that baseline, set checkpoints to see where you're going with your prediction, otherwise you can't compare. And the contracts need to facilitate this."	2.1		"There's a difficulty in trying to predict the future and then being held accountable for that in PPPs. Needs a more nuanced approach to administering the contracts. Otherwise contractors are afraid to lose their shirts and will be over costing. Needs a pragmatic approach, maybe five year reviews."