Bulk Solids Handling-A Chemical Engineer's Perspective

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Abstract

Question. What is the biggest industrial activity on the planet that can quickly and efficiently destroy material value, careers, projects and even organisations?
Answer. Bulk Solids Handling (BSH)

Trite? Intellectually boring? Not relevant to me as a chemical engineer? Think again!
As Chemical (Process) Engineers, our primary purpose is to add value to materials through the building blocks of our profession – unit operations, which are usually found linked up in the form of value-chains. Material flow through a chain governs its commercial success and given over 70% of everything we use or consume passed through a bulk phase at some point in its lifecycle, bulk solids flow is very relevant.

While the science of bulk solids flow is established, it is not widely covered in undergraduate engineering courses, so most of us enter the workforce oblivious to this blind spot. How can we design and optimise value-chains featuring bulk solids when we are blind to the science? The answer is that we cannot, giving rise to value destruction and hence our collective challenge.
This paper explores this often-overlooked enabler of process engineering, addressing issues like:

- Why solids flow is so different to the flow familiar to us – that of fluids!
- How bulk solids flow can impact unit operations?
- Why it has remained a professional blind spot for so long?
- How this blind spot resulted in a $3bn write-down and one of the biggest mega-project failures in history).

1. Introduction

If you are reading this, you already have awareness that the flow of bulk solids is important to Chemical (Process) Engineers and that it is quite different to the behaviour of liquid. This already puts you in the top few percent of practicing engineers, as for most of us, bulk solids flow is a professional blind-spot. A direct consequence of this is that most value-chains featuring bulk solids go into service life with baked-in design errors, which manifest as flow problems during commissioning and go onto plague the operation for its useful life. In this paper we cover the five Ws and How? of bulk solids from a process engineers' perspective with the objective of increasing awareness and promoting adaptation of the underpinning science to the same degree we embrace the science of fluid flow.

2. What are bulk solids?

Bulk solids are defined as materials (solids) that are handled without a count and in large volume. Everything we use or consume comprises of raw materials that must be either grown or dug up and, in most cases before we add enough value to warrant counting items, we need to handle bulk solids.

3. Why is bulk solid handling important?

Consistent with this reality, yet surprising to some, is the fact that BSH is the biggest industrial activity on the planet. It is estimated that 70% of everything we use or consume involves bulk solid handling somewhere in its lifecycle. Bulk solids handling cuts across all sectors and the volumes involved are staggering.

3.1. Shear Volume. While the precise volume of bulk solids moved annually is incalculable, we can used coarse grain estimates to get some empathy**.** For example, each year the Minerals Education Coalition (MEC) [1] determine the lifetime per-capita consumption of common minerals and metals published in the form of their "Minerals Baby" (Figure 1).

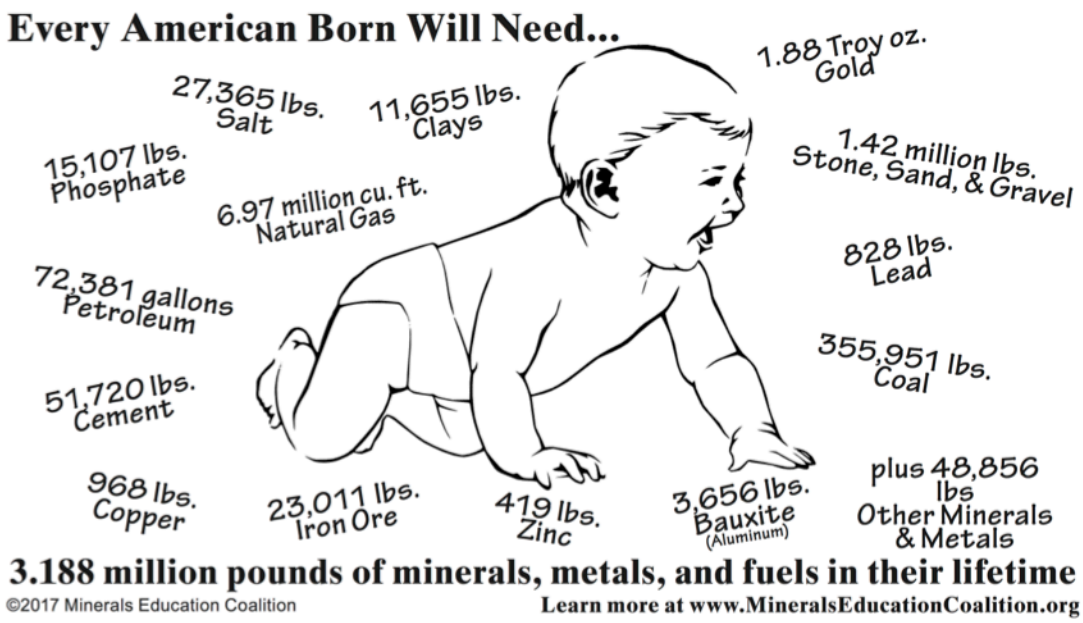

Figure 1: Minerals Baby MEC [1]

Applying some sector specific assumptions in relation to grade, strip ratio (volume of waste rock that needs to be handled relative to the volume of ore) etc, it is possible to estimate the per-capita bulk solids required to keep Minerals Baby fed (Table 1).

Period	Amount of rock that needs to be moved to satisfy the Minerals Baby (adult body masses)
Day	2.5
Year	925
Lifetime	72,900

Table 1: Rock movements required to "feed" the Minerals Baby

In summary, a lot of bulk solids need to flow to keep this baby fed, remembering that any shortfall would impact the standard of living to which we have become accustomed and the situation is not static.

In the mining sector, mines don't get any younger and tier-1 orebody discoveries are getting rare, resulting in a rapid reduction in grade over time. As the grade declines the amount of ore (Figure 2) and waste rock that must be moved to keep pace escalates super-linearly.

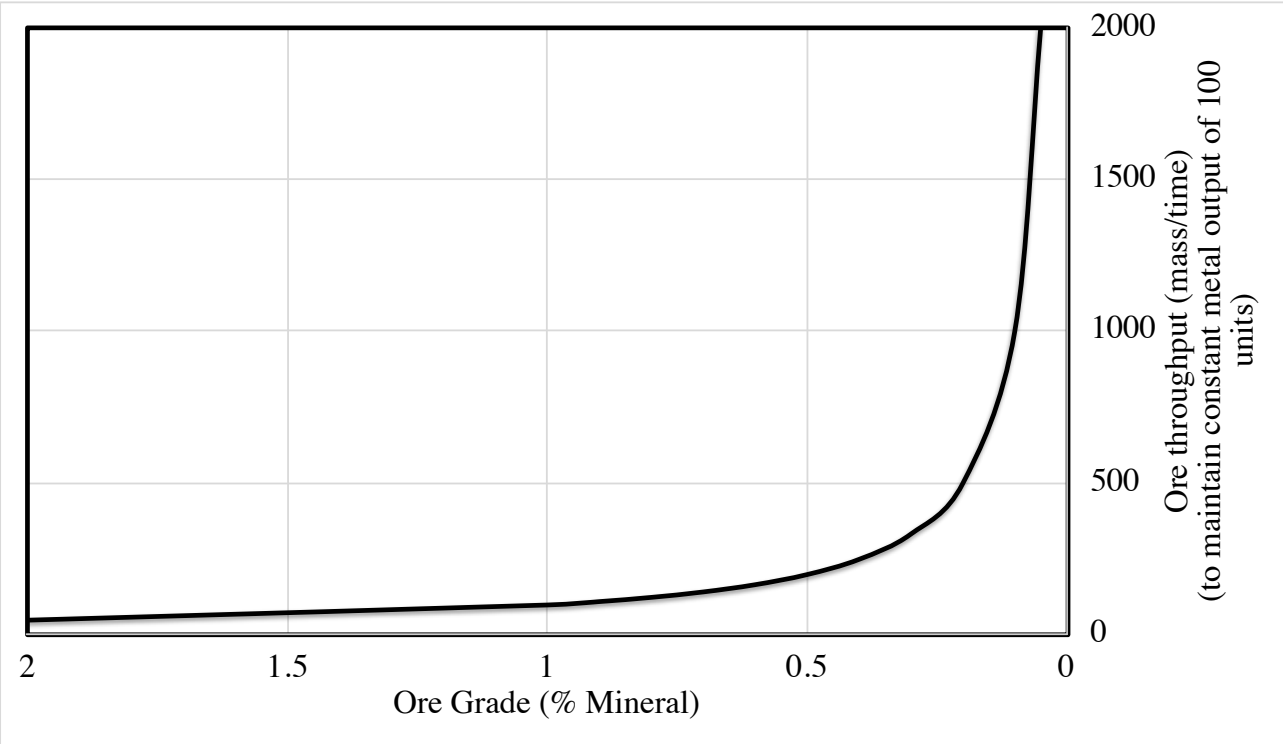

Figure 2: Relationship between ore requirement to maintain a constant metal output as a function of grade.

Compounding this volume issue further is the fact that the minerals baby needs more metal/ore year-on-year as our modern lifestyle changes and urbanisation continues its global explosion.

3.2. Economies of scale

Referring back to the grow it or dig it up origins of common raw materials, it is an interesting exercise to compare the mining and agricultural sectors in terms of the prices their commodities attract in their respective marketplaces.

Consider for example the steps involved in growing fruits and vegetables commercially and then getting them to a supermarket. Now contrast this with the processing/transformational journey (multi-step mining, concentration of the mineral and then chemical conversion/refinement to make the metal, including the liability of the wastes, energy for comminution, ingot casting, transportation, etc)

associated with common metals. The indicative price rankings shown in Table 2 are very likely to be different to the ones arising from a pure process engineering perspective.
The price for tomatoes for example is on-par with copper cathode, which is surprising to many people when you compare at the processing and handling pathways, Other common metals with a similarly tortuous production pathway are even cheaper on a per unit mass basis (Table 2).

For most engineers who appreciate or live one of the mineral-metal production backstories, this is a massive difference in expectations based solely on the process and value-chain "journeys" between a tonne of reasonable purity metal and a tonne of tomatoes, how is this even remotely possible?

Commodity	Price (A$/tonne)	Price Index (relative to iron rebar)	Notes/Reference Indicative trading prices last 6 months)
Blueberries	$39,200	59.4	Coles Online @ A$39.20/kg
Snow Peas	$26,000	39.4	Coles Online @ A$26.00/kg
Baby Spinach	$25,000	37.9	Coles Online @ A$25.00/kg
Cap Mushrooms	$11,000	16.7	Coles Online @ A$11.00/kg
Field Tomatoes	$9,900	15	Coles Online @ A$9.90/kg
Copper	$9,183	13.9	LME-cathode copper ASTM B115-10 – cathode Grade 1 @ (US$6,500/tonne)
Zinc	$3,530	5.3	LME-ASTM B6-12 – LME grade @ US$2,500/tonne
Aluminium	$2,825	4.3	LME-Primary Aluminium (US$2,000/tonne)
Lead	$2,825	4.3	LME-ingots ASTM B29-03 (2009) – Permitted grades: 99.97% and 99.995% @ US$2,000/tonne
Iron (rebar)	$660	1 (by definition)	LME-rebar @ US$460/tonne

Table 2: Marketplace price comparison of common agricultural and mining industry commodities-Ref LME [2], Coles [3]

The reason, of course, is the economies of scale for which the mining industry is famous. For example, the Kennecott Utah Copper mine moves 23,000 tonnes of rock (9,000 tonne ore & 14,000 tonne waste) every hour of every day.

Large mines, large trucks, large furnaces-profitable M&MP is based on economies of scale, but without an efficient way to transfer the bulk solids from and through one-step to the other, the price of the metal product would be significantly higher, making everything incorporating them much more expensive. The application of bulk solids science therefore facilitates the economies of scale that keep the prices of metal low, and we all enjoy the benefit every day. However, before we start slapping each other on the collective backs, we need to look at how much value we are leaving on the table through naïve BSH designs (section 3.4).

3.3. Unit Operations

As a profession, we are collectively fascinated by the process of increasing the value of raw materials (including bulk solids) through physical and/or chemical transformations-i.e. Unit Operations and sequencing of unit operations to create value-chains.
When it comes to unit operations processing bulk solids, there are two areas of interest:

- Presentation of the particles to the transformative instruments/elements within,
- Supplying the feed and removing the products to the battery limits,

Presentation within: Our training has focused us in the design/selection of unit operations in value-chains and then optimising their transformational efficiency during their service life. In

general, we treat unit operations on a macro scale and do not zoom into the level of presentation of individual particles. Given the nature of many transformations, the orientation of the particles presented often matters a great deal. This "bulk solids science meets transformation within the unit operation" is a largely unexplored area with promise to make significant differences to the performance and productivity of many unit operations. Functional BSH-my tip for the future!

Even on the current superficial (envelope) level, our unit operation optimisation efforts are important, as they maximise the potential value-add of the chain, but there is another dimension to be considered.

Flow through the system: Potential is only realised in terms of Revenue when there is FLOW, so Revenue is not only a function of the cumulative value adding steps in the value-chain but is also a function of the effective flow rate through it. As such the full value of optimisation efforts cannot be realised without it.

While it is logical when you see it laid out, it comes as a surprise to many (me included), as I was trained specifically to add value to material, and no one said anything about bulk solid "presentation", "transfers" or "flow".
In summary, when we look at how revenue is generated, many of us are really in the business of flow, and as we will see in section 4, getting bulk solids to flow in a controlled manner takes conscious effort.

3.4. Performance impacts

As process engineers, one of our primary objects is to ensure our value-chains reach (ideally exceed) nameplate as soon as possible and ideally within a few weeks of the date promised (time value of money delays high impact on Net-Present-Value (NPV)).

In the early 1980's, the US Department of Energy commissioned the RAND Corporation to investigate the performance of 37 US and Canadian based processing plants with a view to understanding performance (Merrow [5]). All the plants studied involved chemical transformations to some degree and some featured new chemical routes, there we no new unit operations involved. The value-chains studied also covered the full spectrum of feed, intermediate and product states (liquids, gases and solids).
The headline finding from this very insightful study found:

- Value-chains featuring bulk solids as the main stream performed worse than plants featuring liquids or gases only.
- Two-thirds of these operations (featuring bulk solids) operated at less than 80% of their nameplate (design) capacity at the end of their first year, with a quarter failing to reach even 40%. The average for this cohort was 64% of nameplate compared to 90-95% for the liquid and gas operations,
- In terms of the root causes of these failure, lack of knowledge around heat and mass transfer was the biggest factor. While there are many Heroes of fluid flow, the field of bulk solids flow, which is arguable as important and ubiquitous, is less well researched (Figure 8). As a consequence, our understanding of the transport phenomenon associated with bulk solids is poor when compared to gases and liquids,
- Of the 37 plants studies, only 6% had no major performance issues (defined as a shut-down for one or more weeks during the first year) and the overwhelming majority of problems involved related to process mechanics (bulk solid behaviour) as opposed to chemistry (as per our case study Ravensthorpe Nickel Operation-Section 3.5),
- When compared to plants built in the 1960's (20 years prior) there was no difference (signs of improvement). The improvement effort during that period was found to be focused on

process chemistry as opposed to mechanical processes (understanding flow and doing the bulk solids science homework)

These were considered surprising and disturbing findings at the time and in response Merrow [5] recommended:

- More basic research in support of understanding the behaviour of bulk solids especially in a process environment,
- Characterisation of the actual bulk solids involved in the proposed process-warning against using "library values" that fail to capture the nuances that control the behaviour of bulk solids,
- Feedback (operations back to designers) and clearer accountability for bulk solids flow and behaviour issues in designs. Need to kill they myth that any physical flow problems could be simply dealt with by the operation on start-up.
- Need to give the behaviour of bulk solids equal billing with chemistry in terms of research and development time, debunking the myth that physical flow was trite and not worthy of attention.

Move forward another 20 years and in 2005 Bell [4] reported that value-chains featuring bulk solids typically only hit 40% of stated production rate in the first year, a staggering finding that shows that the dial had not moved at all as a result of Merrow's [5] & [6] findings and recommendations. This finding was made even more poignant by the fact it represented an even wider range of industries (food, nutraceutical, pharmaceutical, chemical, building materials, minerals processing, etc). The common denominator in failure remained bulk solids. The common root cause of this was designers failing to do their homework and differente between the flow of liquids and bulk solids.

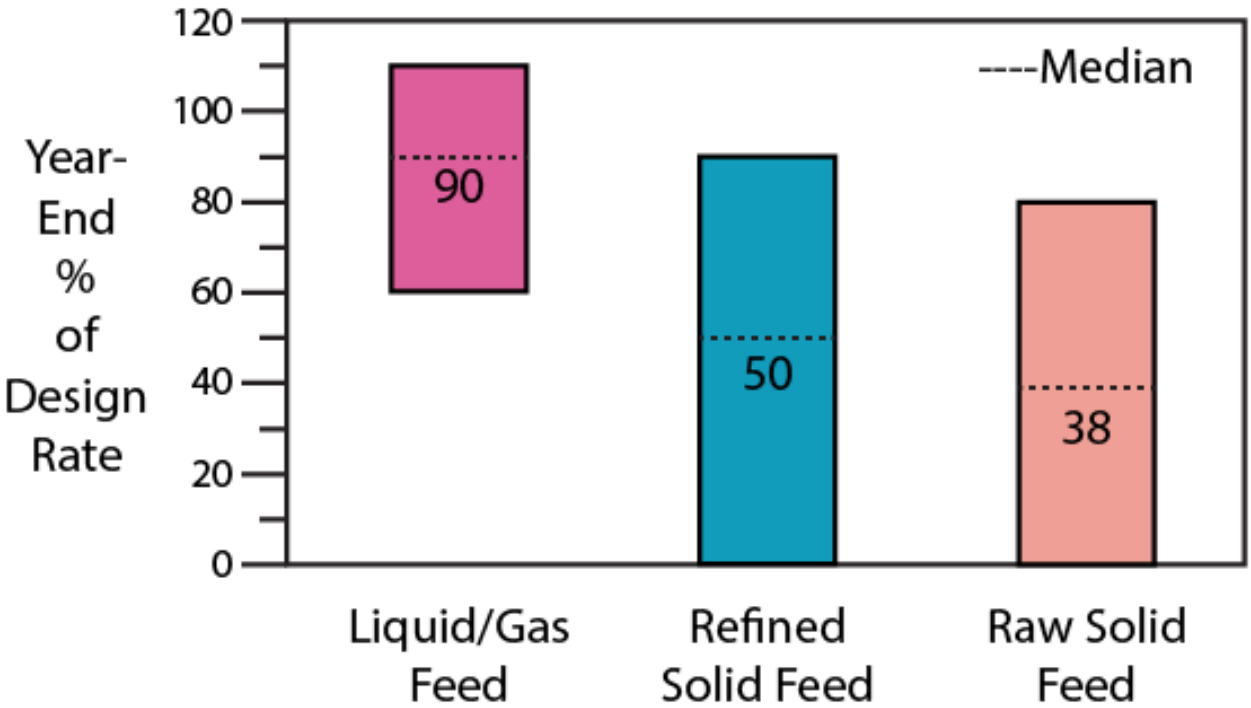

Figure 3: Performance of process plants as a function of feed material [7]

So why is this failure to change so important? Regardless of the finished product endpoint, revenue is directly proportional to the flow of bulk solids through its value-chain (Section 3.3). This dynamic gives rise to one easily measured headline metric: the ramp rate to the basis of design throughput. This metric encompasses all the criteria and describes the value proposition.

McNulty's [7] seminal research into this performance metric in the mining and mineral processing sector yielded the infamous McNulty Curves, which have proved accurate in predicting a project's ramp rate trajectory as a function of the flowsheet novelty and study phase quality. Projects where the study phase homework is incomplete and/or those featuring multi-step processing and chemical transformation(s) are consistently the worst performers.

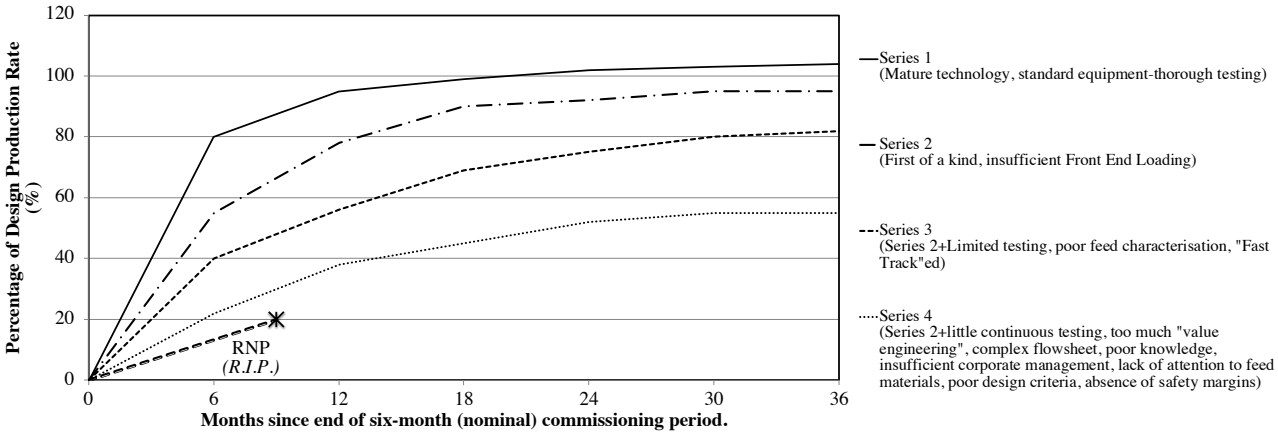

Figure 4: McNulty Ramp Up Curves [7]

In the context of the McNulty curves, the plateaus represent the long-term average production rates as which shown in figure 4 are often much lower than nameplate.
One of the reasons for the sub-optimum plateaus is that after a while the negative impacts of bulk solid flow are normalised and factored into daily production targets and personal goals, masking the opportunity and further reducing the incentives for corrective action (if we hit target, there is no problem-and if it ain't broke, don't fix it).

Yet another performance characteristic of a value-chain featuring bulk solids is that unlike operations based on liquids, the instantaneous rates are usually far from constant giving rise to the Perfect Production Day run-chart proposed by Wellwood [8], a typical example of which is given in Figure 5.

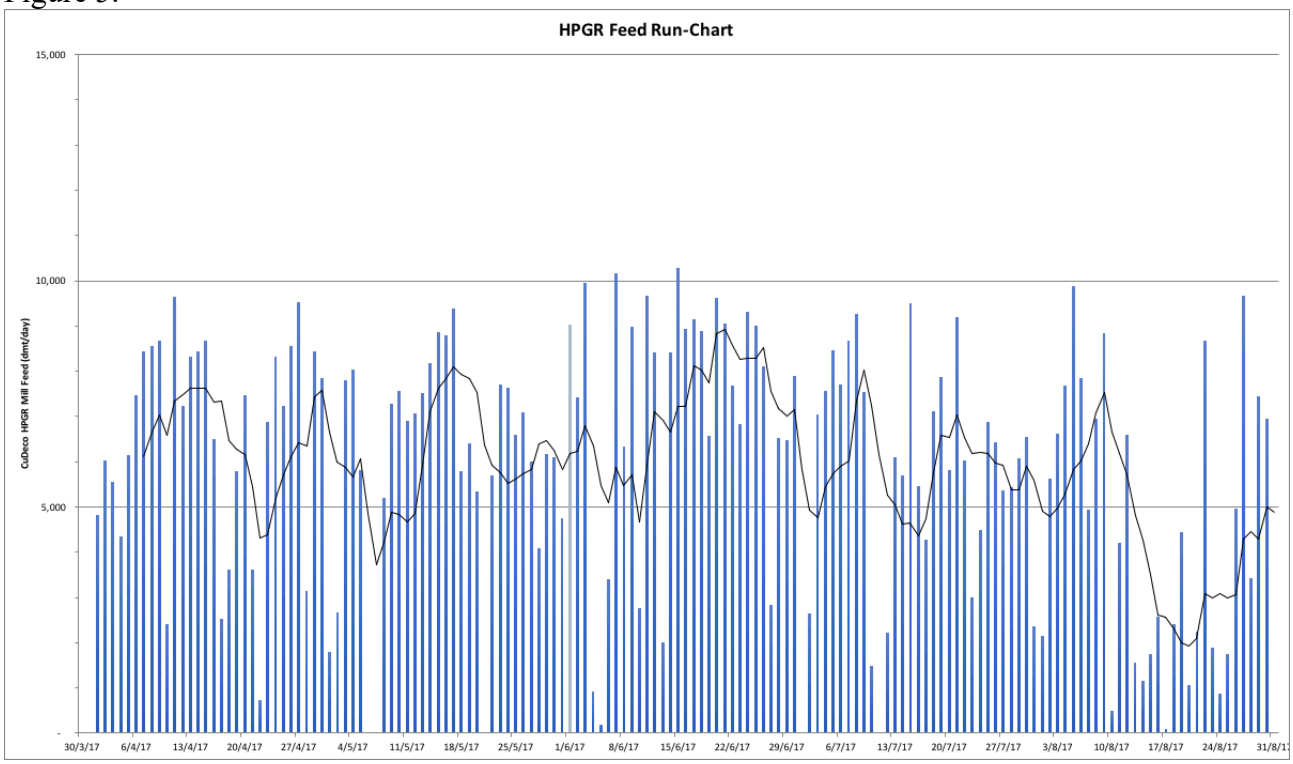

Figure 5: Perfect Production Day

While its noisy form is usually no surprise to operations people, it can be confronting to head office types seeing this type of chart for the first time. The typical response is to go into denial, saying that their operations are different, and their charts do not look anything like Figure 5. This is normally because the information they get is heavily aggregated, but when they get down into the weeds, and take a closer look, they see this is exactly what they have-much to their surprise. So, their natural question is why cannot every day be perfect?

In this common situation there is no real driver for long-term corrective action (sometime referred to as the 100-year fix). Instead disruptive flow events like blockages and stoppages tend to be treated as "spot fires" and dealt with immediately in a reactive, let's get the show back on the road, manner by means of a quick fix (corrective action). The good news for process engineering profession is that there is a lot of scope to make a material difference to operational revenue and productivity and in the case of new operations to deliver significant value to shareholders by efficiently and sustainably ramping up to nameplate.

3.5. Case study: Ravensthorpe Nickle Project

To help make these value impact more meaningful, it is useful to consider a case study. The Ravensthorpe Nickle Operation (RNO) project is a very relevant, recent (10 years) and poignant case study in BSH. Those who ignore history are doomed to repeat it!

The Ravensthorpe Nickle Operation (RNO) was a flagship M&MP project for the world's largest mining house BHP Billiton (BHPB). The Basis of Design (BoD) was to produce 50,000tpa Ni equivalents from a Saprolite (30%)/Limonite (70%) ore via a new combined (pressurised acid leach [PAL] and
atmospheric leach [AL]) leaching step called Enhanced Pressure Acid Leach (EPAL).
The scope of the project included development of a mine, processing plant and associated infrastructure near Ravensthorpe in Western Australia to produce the mixed nickel cobalt hydroxide intermediate product (MHP) for processing at the company's existing Yabulu refinery, whose accommodating capacity expansion was also in the scope of this mega-project.

In 1997, the project entered a study–phase which was to last seven years and pass through the standard pre-feasibility and feasibility stages (Figure 6). The salient features/achievements of the completed RNO study–phase included:

- $85 Million-Front End Loading (FEL)
- 200,000 engineering-hours
- 8 months continuous pilot plant operation,
- ore blends covering Life of Mine [20y] evaluated,
- 5 independent technical reviews (IPR's),
- Rigorous internal processes (including hydrometallurgical expertise from alumina business),
- Detailed mine planning

Figure 6: Ravensthorpe Nickel Project Key Event Timeline

The RNO emerged from its final study–phase gate (4) in March 2004, with approval to proceed at the cost of US$1.04 billion(bn). In the context of this announcement, the project was promoted to investors as having the best possible profile for any greenfield laterite project as it was expected to provide the high leach feed grade with low mining costs.
The detailed design and construction phase of the project started immediately thereafter with the appointment of two world class Engineering Procurement Construction Management (EPCM)'s. Unfortunately for everyone involved (directly and indirectly) in January 2009, BHP Billiton announced that it was suspending production at the Ravensthorpe nickel mine indefinitely as this mega-project had failed on all its metrics (Table 3 below).

Performance Metric	Expected	Actual (at point of suspension Feb 2009)
Capital Cost	$1.4bn (approved)	$2.1 bn (110% over run)
First production	2006	Q2 2008 (18 months late)
Nameplate	50,000 tNi eq/y	20% Nameplate (Langridge, Frigger, & Claflin, 2018)

Table 3: Summary of RNO against its headline success criteria

At the point of its suspension in 2009, RNO has only reached 20% of its design capacity (plotted as the * on Figure 4) and was registered as a $3.615 bn impartment to BHPB with over 1,800 job losses. The Ravensthorpe operation was eventually sold to First Quantum Minerals Australia Pty Ltd, for US$340 million and after an extensive 18 months of modifications and refurbishment, was operated profitably.

While there were undoubtedly market related issues (Department of State Development [9]), the root cause of the failure was really a technical one; the operations inability to achieve its nameplate throughput in a sustainable manner. Although the core transformational step in the operation (combined acid and pressurised leach) performed exceptionally well, it was starved of feed (maximum sustainable throughput only 20% of BoD nameplate capacity) because of front end materials handling problems baked into the final design (Piper [10]), (Moore [11]).
The very word "Laterite" comes the Latin word for "brick" or "tile" which refers to the utility of the clay content and the standard dictionary definition is; "a reddish clayey material (read sticky), hard when dry, forming a topsoil in some tropical or subtropical regions and sometimes used for building."
So how did a project managed by the world's largest mining house and with such an extensive study–phase fail so spectacularly, from what was subsequently revealed as known and demonstrably addressable causes?

4. Professional Blind-spot

Process engineering is in essence a dynamic field where flow (particulate solids, liquids and/or gases) through the value-chain underpins everything we do (section 3), however for most of us, the fact that bulk solids flow differently to liquids is a classic blind spot (Figure 7).

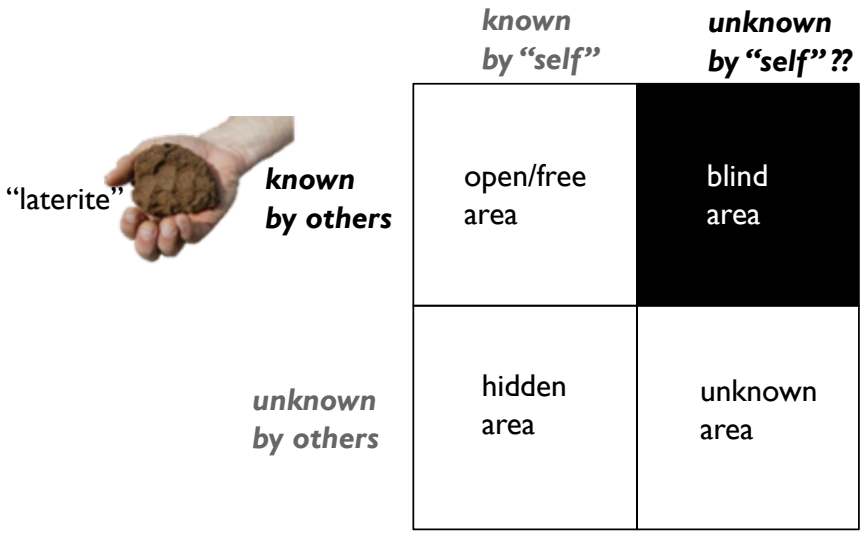

Figure 7: Johari box

Grated, the flow behaviour of liquids has been the subject of intense study by a start-studded cast of generous engineers and polymaths for over 450 years (Figure 8), but thanks to the efforts of Jenike [12] [13] [14], there is a well-established and accessible science underpinning the flow behaviour of bulk solids.

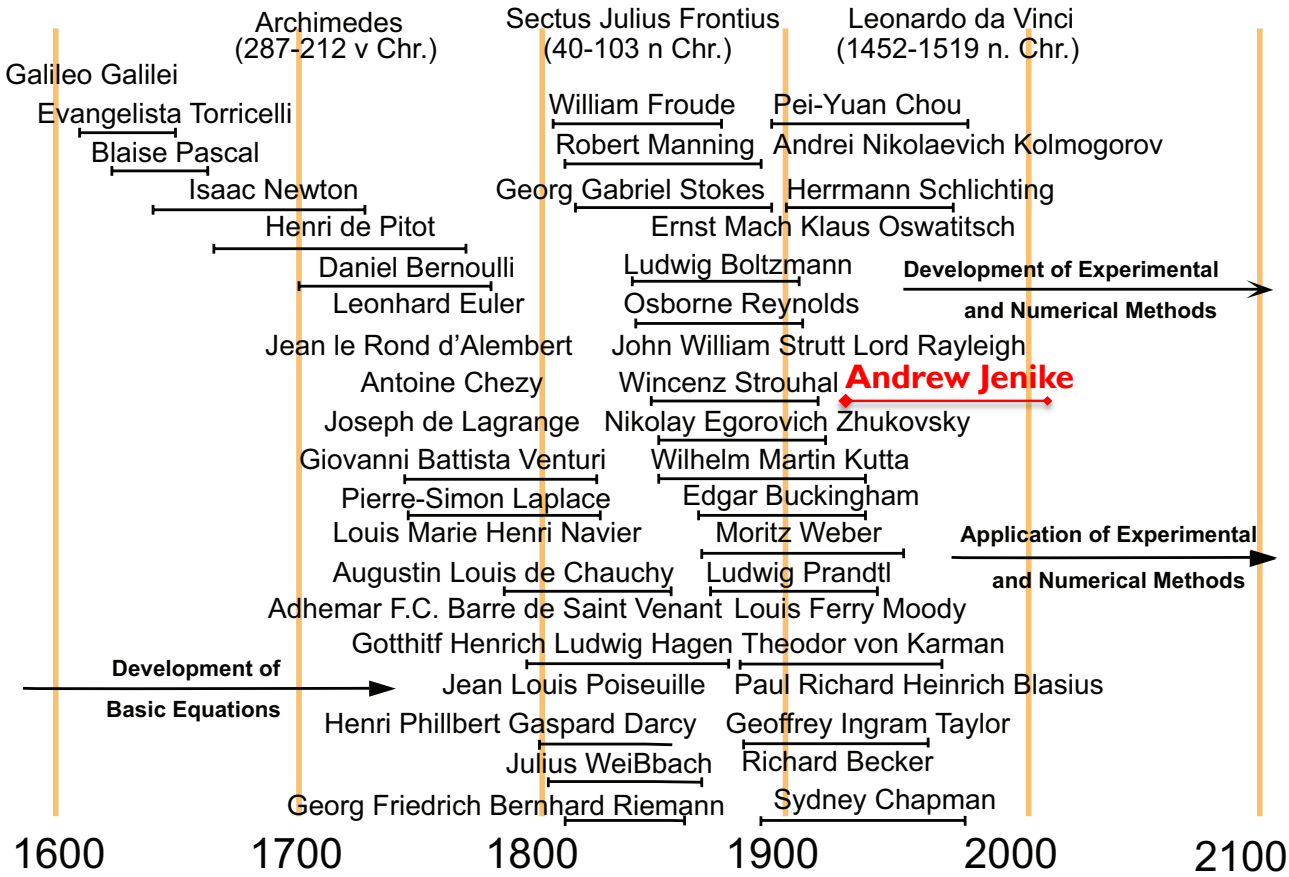

Figure 8: Our Heroes of Flow

So why is it such a blind-spot for process engineers? As stated earlier our profession is all about transformation and value add and bulk solid flow does none of this by design. Bulk material flow elements (bins, feeders, chutes etc) are not unit operations. Simply handling bulk solids does not increase its material value and it's often not considered technically challenging or important enough to dedicate your career to (unless you have been enlightened), which all manifests in the fact that it is not covered in undergraduate curriculum. In 1986 the British Materials Handling Board surveyed all mechanical and chemical engineering departments (universities and polytechnics) in the UK regarding the treatment of bulk solids science. No mechanical engineering department surveyed at the time included a single topic on bulk solids handling and/or particle-fluid interaction and while chemical engineering departments fared better (most included a topic on particles), in relation to the other 3 phases of matter (massive solids, liquids and gases), the effort was effectively tokenistic. So why do we have this disconnect between our education and such a common and for many of us important profession demand? Some reasons cited include:

- Bulk solids are perceived as being "low-tech" (see previous comment not-sexy),
- Experimentation is essential as a purely computational approach (as per the undergraduate treatment of liquid and gases), while the long-term goal, is unrealistic,
- They are usually complex and adaptive hence not easy to define mathematically or in terms of their physical properties,
- Characterisation of key performance parameters like flow function require specialised testing units, experienced technicians (compare to a viscometer for example) as well as time to complete,
- Bulk solids are more problematic (messy, heavy/awkward ect) to deal with in a laboratory settings-See Table 4 for most unsavoury characteristics,
- Design methods are less developed and/or maintained as trade secrets

All-in-all these practical challenges tend to deter academics from entering the field themselves and/or teaching the science at undergraduate and postgraduate level.

This professional mindset is reflected in the treatment of the subject in Perry's Chemical Engineering Handbook (aka The Chemical Engineer's Bible). Before the Internet, this tomb was the knowledge repository of our profession (Figure 9).

Figure 9: Perry's Chemical Engineer's Handbook over the ages-with respect to bulk solids handling and science content

First published in 1934 with 8 editions since, it has been a source of chemical engineering knowledge for chemical engineers, and a wide variety of other engineers and scientists, for more than 85 years.

The scant treatment of the BSH is not commensurate with the planets largest industrial activity that cuts across so many sectors and processes of interest to process engineers, but it does reflect undergraduate curriculum and helps explain our collective blind spot.

5. How does bulk solid flow differ from fluid flow?

Having established that bulk solid flow is important for productivity and revenue in many process engineering theatres, what exactly are we talking about? Let's start with the most familiar understanding of flow, that associated with liquids.

5.1. Fluid Flow

For all intents and purposes, flow behaviour of liquid is characterised by a single value, its viscosity, which is usually only a function of temperature. Know the temperature-know the viscosity-know the flow behaviour, and there is no need to measure the viscosity of the fluids yourself. If you know the fluid and the temperature, you can easily look-up its viscosity (Figure 10).

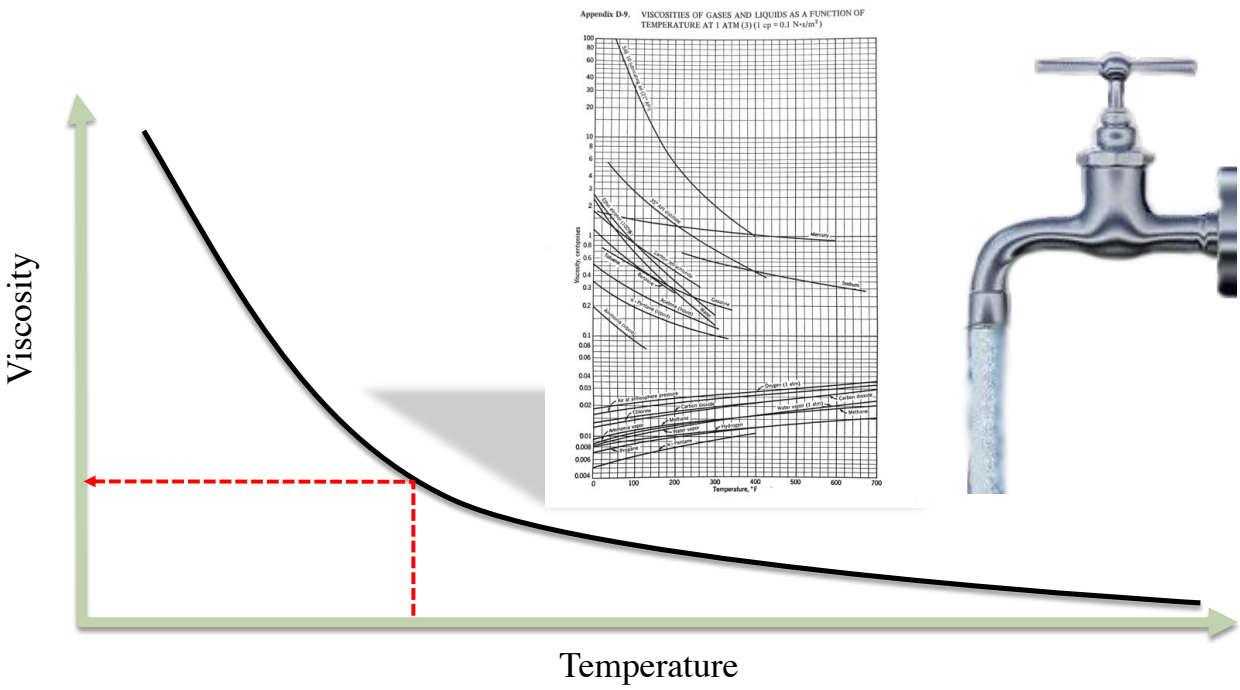

Figure 10: Liquid viscosity-temperature

Sadly, this simple and familiar framework that allows us to engineer the controlled flow of liquids does not apply to bulk solids.

5.2. The nature of Bulk Solids

Unlike fluids, the movement of bulk solids is controlled by friction (particle-particle, particle-surface), and every discrete element (from dust spec to boulder) in an unrefined (raw) solid feed (like ore), is physically and chemically unique. Consequently, the flow properties change, often dramatically, depending on the complex interactions between particle size and distribution, moisture content and distribution, process history (time and manner), mineral composition, surface texture and condition as well as ambient conditions, just to name a few! According to the three headline behaviours below, bulk solids can be considered at 5th state of everyday matter viz:

- they are not solid, although they can withstand some deformation,
- they are not liquids, although they can be made to flow,
- they are not gases, although they can be compressed,

As process engineers we are most interested in the controlled movement or "flowability" of a bulk solid which is also function of the design and general arrangement of the handling equipment and associated materials of construction. For example, an "easy" or free-flowing bulk solid placed in a wrong piece of equipment can become difficult to handle; whereas material that appears to be hard to handle (for example sticky), placed in the correct equipment, can flow reliably. When considering bulk solids, it's always important to take a holistic or "systems" view.

For a profession used to dealing with predictability and control, the flow behaviour of bulk solid can be quite confronting, and you often find yourself scratching your head in amazement at what you see in practice. This sentiment is captured in Table 4, which builds on the playful (yet poignant) characterisation framework developed by Woodcock & Mason [15].

Behavioural Disorder	Manifestation
'Neurotic' materials • poor flowability • excess flowability • stick-slip flow • are sticky or tacky • tend to pack or bridge • can form piles & shear faces • impact, bouncing, rolling	*they move awkwardly*
'Sadistic' materials • abrasive • corrosive • toxic • explosive • heat source/sink (high heat capacity) • dusty • adhesive	*they attach their surroundings*
'Masochistic' materials • friable • degradable • contaminable • absorption (*chemi-* & *physi-*) • caking • wall friction • sensitive to applied pressure	*they suffer from their surroundings*
'Schizophrenic' materials • hygroscopic • susceptible to electrostatic charge • segregation • fluidisation • shear thinning (when aerated &/or saturated) • asymmetry	*they change their behaviour pattern*

'Dementia' materials • compacting-interlocking • deaerate/permeability • phase separate (entrained gases, water..) • salt bridging • settling/consolidation (Hausner ratio)	*they change their behaviour with time*
'Borderline Personality Disorder (BPD)' materials • sensitivity to particle size & distribution (e.g. Geldart grouping) • surface texture • surface chemistry • shape	*they are often hyper-sensitive to small changes-impulsive, unstable-reckless!*

Table 4: "Psychological" profiling of bulk solids

Note just like their real-world human presentation, condition can apply simultaneously, so life is seldom boring when you are dealing with bulk solids!

5.3. Bulk Solids Flow-Strength

In essence, it's all about achieving flow control. As shown in sections 3.4 and 3.5, the inability to control the flow through the value-chain can be far reaching with the potential for significant impacts on product quality, production productivity, maintenance/operating costs, the environment and even safety. The good news is that the science required to control flow in the face of such large natural variation, developed by Jenike [14] is well established.

Flowability of bulk solids depends on its Strength and the Shear that is applied. Strength is determined by things like friction, mechanical interlocking and cohesion; hence it cannot be pinned down to one factor analogous to viscosity, and the relationships are not linear. For example, consider the property of moisture content in the context of beach sand. Dry sand flows well but start adding water, and at some point, the particle-particle cohesion reach a tipping point, and in a blink of an eye, the material will suddenly stiffen up and start to behave like a solid-essential for sand castles but not good for flow. Continue to add water and it will eventually start to flow again, as the water lubricates the system on its way to becoming a slurry. Moisture is just one of many factors important to the strength, in general all the influencing properties depicted in Figure 11.…operate locally & on a small scale, are Non-linear, and are sometimes Interdependent.

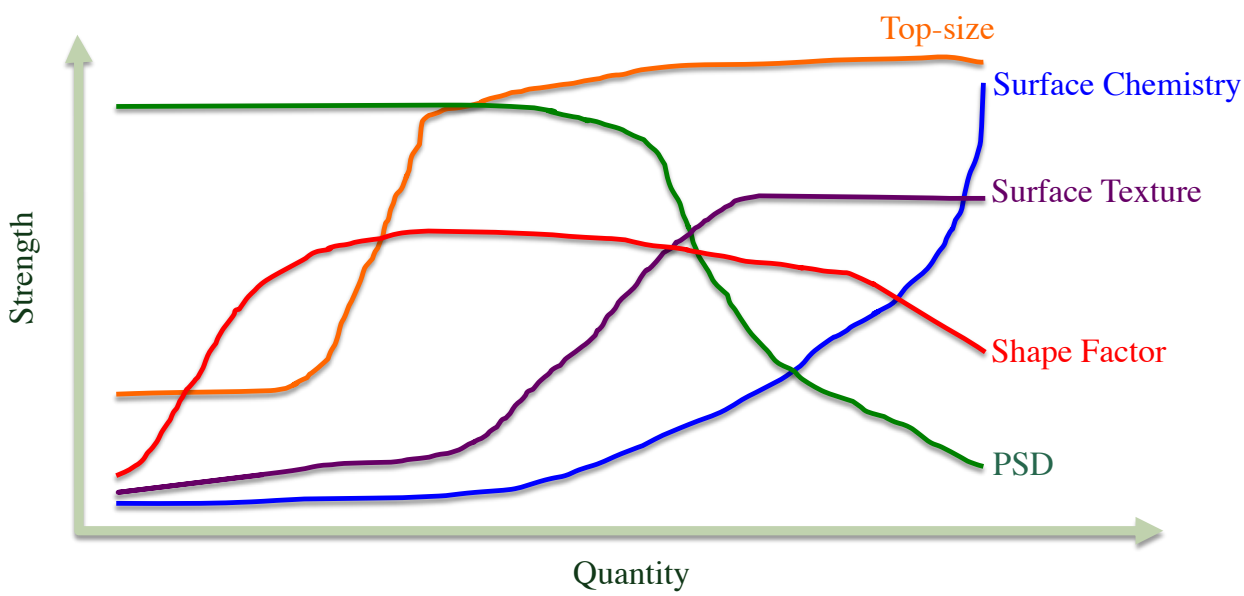

Figure 11: Impression of how the strength of a bulk solid varies as a function of its properties which are non-linear and involve multiple influences

In the case of operations like mining, we are dealing with a natural solid, where every individual particle is unique, meaning none of its properties are a constant value and instead exist as ranges between limits (Figure 12).

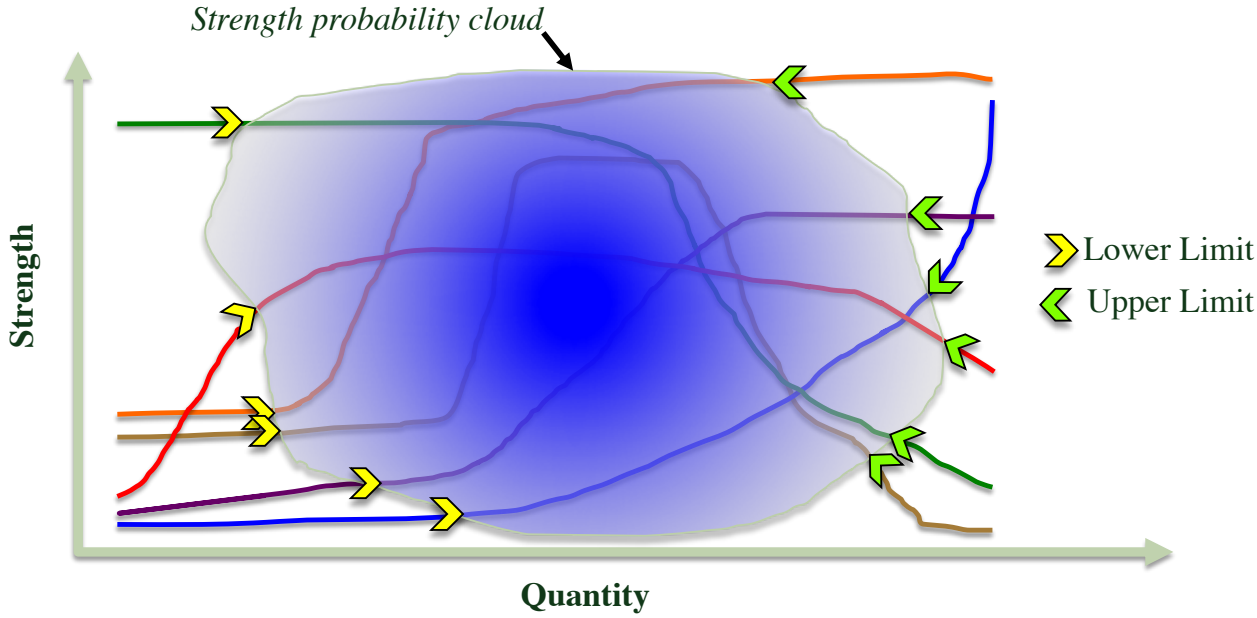

Figure 12: Probability Cloud mental model for bulk solid strength

At any moment in time, the properties of any shovel-full of raw solid, could be anywhere within its range. So, when we add the dimension of time, we get a Strength probability cloud and time weighted hot spot (Figure 12).

5.4. Bulk Solids Flow-Fixed Plant

But flow behaviour does not end with the Strength of the material itself. Bulk solids will only flow when the induced stresses exceed its strength, so it also depends on the fixed plant. To illustrate, let's take a common flowsheet element like a bin.

The 3 common design choices in relation to bins are,

- Shape; should it be round, square, or rectangular?
- Angles; because within bins we need to converge flow and induce stresses,
- As well critical dimensions-that determine capacity and site space requirements

While they are all definable, there are also interdependencies.

In most situations, sliding surface is also important,
and here are the 3 major design choices

- Physical surface finish,
- Surface chemistry
  and
- Resilience-the ability to simply remain in existence and maintain these properties during service life

In the detail design stage, all these options are specified to define the For-Fabrication device

However, these critical choices are often made at arm's length by our preferred Engineering-Procurement-Construction (EPC's)/ Engineering-Procurement-Construction Management (EPCM's) partners or their OEM's, and often in a "flow behaviour" vacuum based predominantly on lowest capital cost and/or available space (i.e. an afterthought).

This raises an interesting philosophical point; just who is accountable for the performance if flow properties are not provided in the basis of design?

6. What are the warning signs?

Flow issues have always plagued value-chains featuring bulk solids and despite the causes being flagged and the availability of the solution science, the problems persist. With awareness that controlled flow of bulk solids needs special treatment, it is useful to flag some common root causes to look out for.

- Failure to measure the flow properties of the site-specific bulk materials to be handled and therefore properly inform the Basis of Design (BoD)-the single source of truth for all ensuing design activities.
- Where such data is given in a BoD, it's quite often not measured but lifted from "library values" to avoid the effort and costs of testing. While this is common practice for fluids, it simply does not hold for friction controlled bulk solids and can turn out to be a very embarrassing false economy. An Iron Ore based example is the specification of BSH elements required to handle magnetite concentrate designed on the library values of hematite (Tan et al [16]).
- Pilot scale work is sometimes conducted on material blends that cannot be practically replicated in the production environment. This test work has a different agenda so the samples used may not be representative when it comes to quantifying flow behaviour.
- If the operation involves blends downstream, they most certainly need to be included in the materials characterisation program together with their upstream constituents. Because behaviour is friction controlled it is it is not possible to accurately predict performance of blended solids based on the properties of their constituents' materials.
- In a similar vein the testing program should also include side and dosing streams as flow control problems here can just as easily constrain operations.
- While some processes as predominately "wet", they can still have "dry" front ends, where bulk solid flow issues need to be addressed. Unfortunately, this reality is sometimes overlooked by development teams giving rise to operations throttled by the performance of their front end. The RNO example (section 3.5) is a high-profile example of this phenomenon (Piper [10]).
- Project NPV is sensitive to the duration of the study phase so there is typically great pressure to accelerate ("fast track") proceedings, often at the expense of completing the necessary "homework" (Sanborn [17])- unfortunately the idiom "haste makes waste" hold true in bulk solids handling.
- The BoD must consider the material through the life of the operation, not just its early life. For example, if a mine needs to go below water table some years down track, is the plant capable of handling the increased stickiness? The data defining material flow characteristics over the life-of-mine should be considered as important as the mineralogical and metallurgical aspects of the ore body knowledge used to test projects at each stage of their progression through their study phase to the final investment decision (Sanborn [17]) and then inform the detailed design process,
- Bulk solids science is complex and not usually included in undergraduate engineering courses. It is therefore a specialised skillset that is not normally (and understandably) held in-house. As such awareness that there is a potential problem and how to address it can be an issue (section 4)

- While they can quickly and effectively destroy value, bulk solid handling elements like bins, transfer chutes, stockpiles, conveyors and feeders are not unit operations and hence do not add value (materials are not intentionally transformed). As such during the study and detailed design phases, where the focus is on maximising value, the subject of bulk solid flow is often treated with contempt at the expense of the high-profile unit operations (crushing, screening, washing…) that add value to the material being processed and come in at higher capital cost.
- Failure to recognise the interdependence between bulk materials and the general arrangement and construction materials of the devices designed to handle them,
- Failure to recognise that most items in the flowsheet can impact the performance of BSH elements downstream. For example, stockpile segregation can impact things like bin flow and transfer chute performance,
- Lack of accountability- Just who is accountable for the ultimate performance of the materials handling system (owners' team, study teams, Engineering-Procurement-Construction (EPC's)/ Engineering-Procurement-Construction & Management (EPCM) partners, contractors, equipment vendors etc)? Compounding this is the fact that best-practice is to pass projects through a number of formal stages/phases on their way to approval. How does the accountability transfer at these points, given the teams involved can change between phases as well as over the traditionally long development period? Despite advances in the management of mega-projects, lack of continuity in study teams, especially between phases, is still being cited as a common failing (Duinker [18], [19]).

7. How do you approach it?

Awareness is the first step and we are all now in the "Open" quadrant of the Johari box. For many engineers, visual mental models are useful constructs for dealing with complex systems and value-chains featuring bulk solids can be depicted as in Figure 13, as a series of process steps connected by transfers, each with its own material strength cloud (blue) and sweet spot (green diamond) determined by the hardware design.

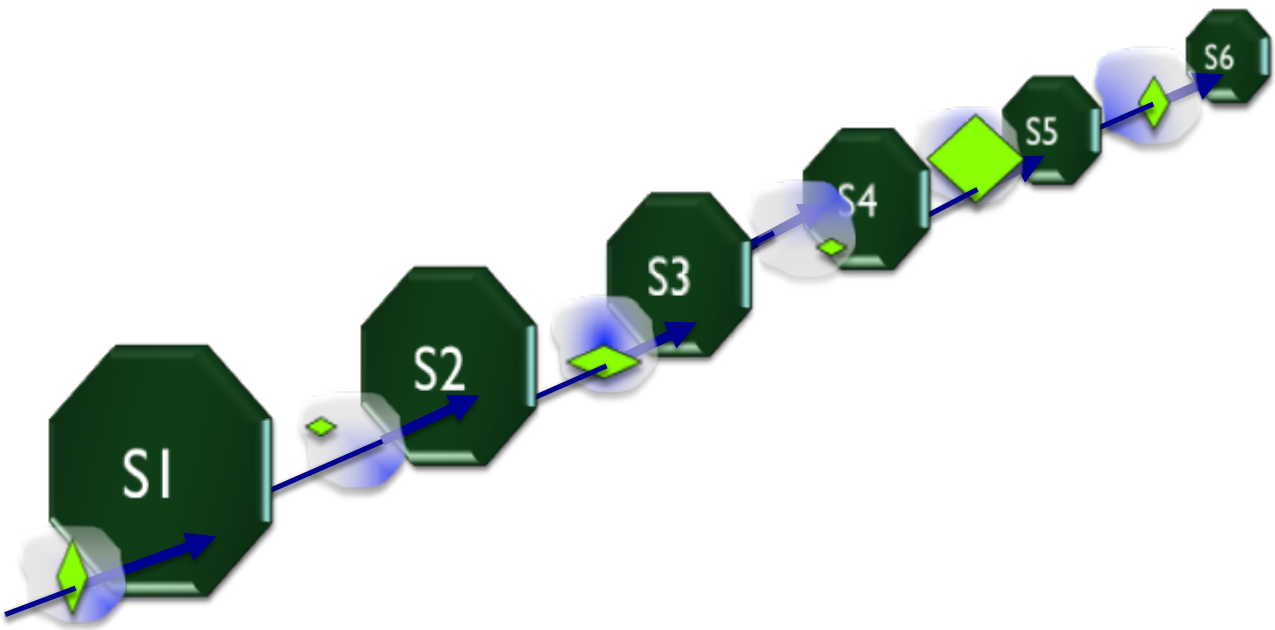

Figure 13: Mental model of a bulk solids processing value-chain

In this example the transfer between steps (S)1 & 2 has a small "sweet spot" (shown by the green diamond) located away from the region of highest probability (darkest blue region of the cloud), meaning it is going to be a regular controlled flow problem. The transfer between Steps 4 and 5

however is well designed and has a generous sweet spot that nearly cover the cloud, we you would not expect flow problems here, and so it goes along the rest of the chain.

Because the value-chain is only as strong as its weakest link, in terms of Product flow (exiting S6), we would get a very erratic outcome, (just like the daily production chart Figure 5), as the material characteristics at each transfer point move in and out of its sweet spot over time and to those who operate it? a game of down-time wack-a-mole; but without the prospect of a stuffed toy.

7.1. Existing Plant?

Tempting as it is to spring straight into action when there is a bulk solid flow problem, to do so without the science is to repeat the mistakes of the past that caused the problem in the first place.

While time is of the essence when flow is out of control, when it comes to solid flow problems, you need to go slow to go fast. A simple three step strategy that is both useful and defendable in the face of those who say, "Don't think, Just do!" is shown in Figure 14.

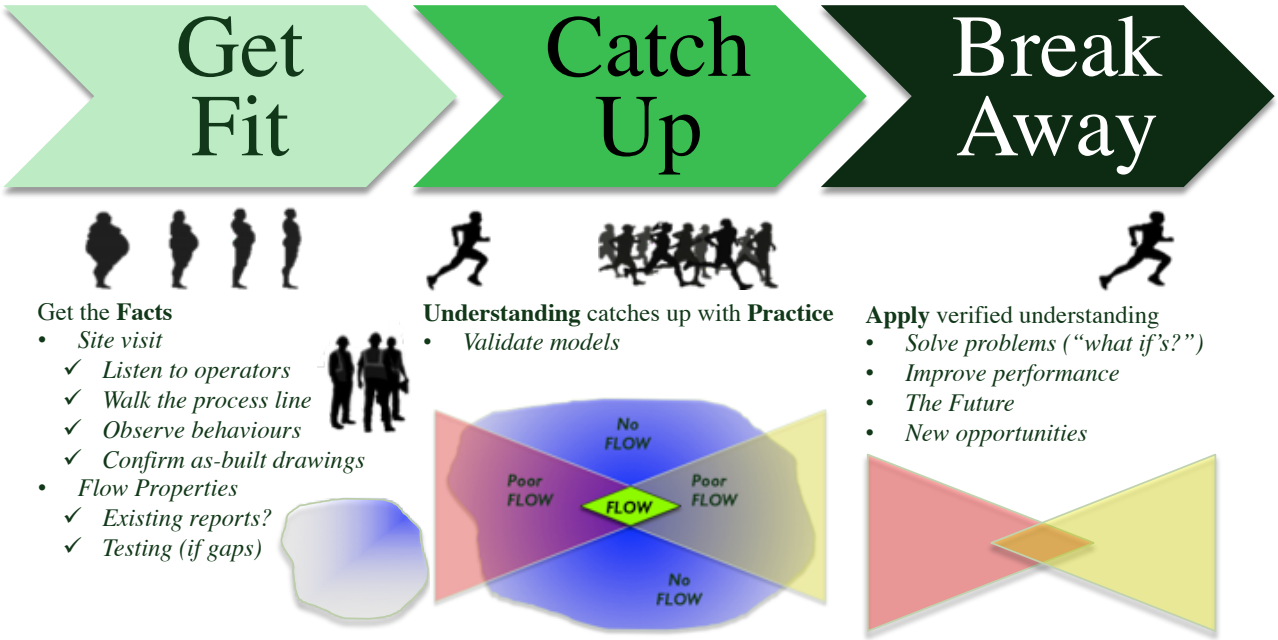

Figure 14: Three Step Strategy for dealing with flow issues in an existing value-chain

- First **Get Fit**. Get the facts, understand your situation and if necessary, fill in the gaps by testing your materials.
- Next **Catch-Up**, make sure your understanding of the situation lines up with current practice. The science of bulk solids flow is usually applied via models (physical and mathematical), but if the configured models cannot predict the current situation, they are going to be worse than useless in forecasting the outcome of change
- The final step is the **Break Away**, using the validated models to solve problems and consider the "What ifs".

But even validated models are just tools, they cannot generate solutions in their own right, and they need creative input from humans in the loop. In terms of levers, we cannot engineer the material characteristics, so "what ifs?" normally involve trying to broaden the equipment sweet-spot, however for installed plant, the options can be limited.

In summary in addition to being the one to spot flow as a root cause, this is where process engineers can add real value, using the model to consider the "What if's" in the model/virtual world, to converge on long term solutions for the real world.

7.2. Automation & BIG data to the rescue?

As we know, there are a lot of Productivity Silver Bullets flying around these days shrouded in all sorts of hype. Automation, and the Digital Twin, both sound great, but what do they look like when you consider them from a bulk solid flow perspective? Most of these Silver bullets are unit operation focused, and treat flow as invariant, so automating a plant with material flow problems, like the one represented in Figure 5, will just give you Automated flow problems!-because we have not addressed the physical root causes of poor flow.
With automation comes the loss of our unsung Downtime Heroes who normally keep the show on the road, so we will probably make things worse, and there are already signs of this appearing.

A digital operation where nearly every physical parameter is measured might give you system insights based on patterns (inferred models), but many of the recommended actions arising have flow implications right through the chain, hence may not be implementable, or if so will have unintended consequences. For example, an optimisation insight may call to increase throughput by 10%-simple enough? However bulk solid transfer points usually have a finite and very sharp defined volumetric capacities with small contingencies (if any) so 10% could be enough to cause it to choke, a condition that is often not reversible (i.e. it will not disappear if the rate is backed off-it is time to shut down the line and break out the shovels!). Further any change to throughput usually involves changing the velocity of the stream (speed of the conveyors), which can have numerous downstream impacts including increased wear rates, asymmetric loadings (of screens, bins, chutes), increased attrition/dust, loss of containment, increased segregation, wall build-up (due to increased pressure).

Until BSH fixed plant can respond physically to changes in condition and accommodate actionable insights, the focus needs to remain on deterministic models and ensuring our design sweet spots cover as much of the bulk material's current (and future) strength probability cloud.

8. When should the science be applied?

The current situation with respect to controlled bulk solid flow is generally a reactive one, where the science is being applied retrospectively to try a remedy faulty designs (section 7.1), but as a profession we need to break out of the cycle and get proactive.
Awareness is the first step and now we are out of the Johari Blind Spot quadrant into the Open (Figure 7), when do should the science be applied? As early as possible! If we accept that many of us are in the business of flow, achieving controlled flow by design should be our top priority and we have maximum influence at minimum cost during study phase (Figure 15). Having someone with BSH expertise at the design table will help you identify all possible options (often the best ones are from in another industry that has solved the problem for a "like" material) and then converge on the best one for the go-forward design. The default option (if there is one) is seldom the cheapest or the best one for long term productivity.

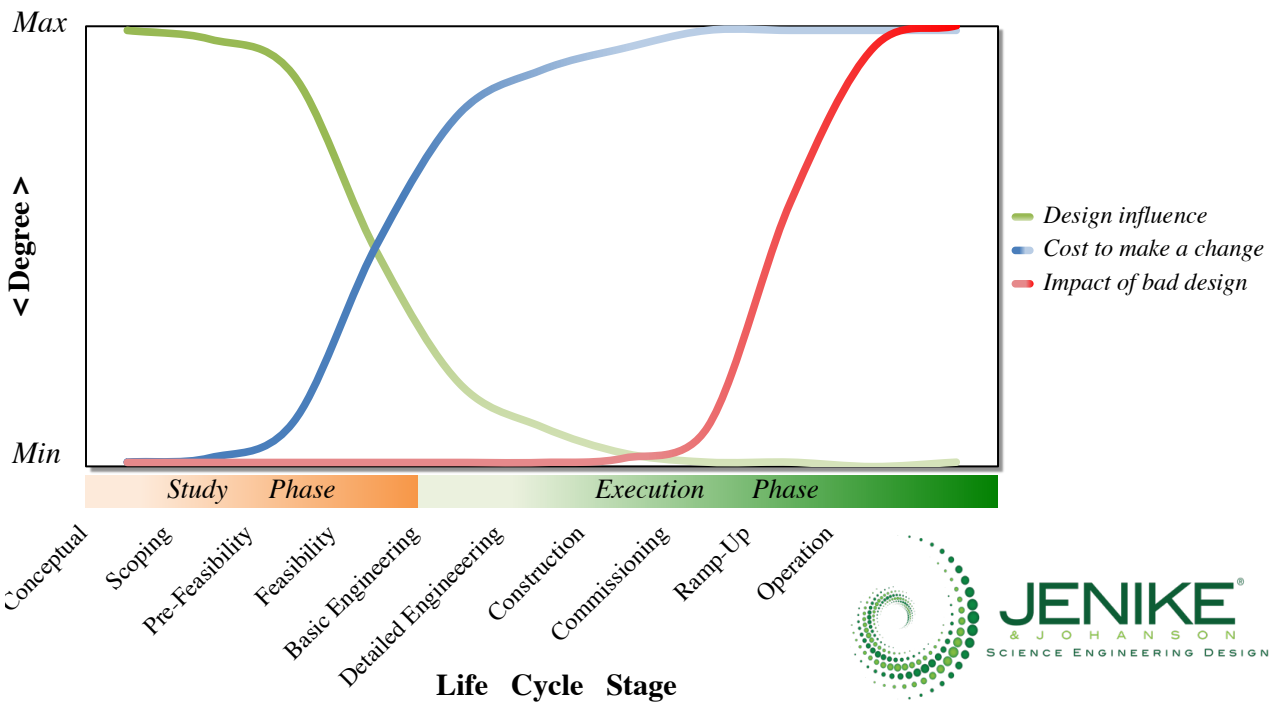

Figure 13: Impact of Timing

Once the final design is locked in, the cost of rectifying it kicks up steeply and during commissioning the flow problems themselves rear their ugly heads in the form of life-of-asset financial and operational impacts, that of course is only if they don't morally wound the entire operation beforehand (a al RNO).

9. Who should be involved?

For many organisations, it makes good business sense to ensure their bulk solid flow decisions are independently informed by science. Maintaining a full-time expert in-house is often the obvious option, but there are alternatives. In terms of accessing the bulk solids expertise to achieve this, there are four broad brush options:

- **Insourcing**: Employing the expert as a full-time staffer who then provides the service from within the organisation to its internal clients. The expert reports and is managed by the client organisation (think technical departments-which can be either corporate or assigned to a specific business unit). Historically this has often been the instinctive option, but there are others.
- **Outsourcing**: The expert is employed by a third-party organisation and is made available (engaged) on a per-assignment basis according to the terms of a service specific contract. The expert in these situations reports up through and are managed by the third-party organisation (think consultancies). The emerging phenomenon of accessing professional service via the "gig economy" (as part-time, temporary and freelance jobs) has also been included under this banner. Superficially supplier expertise also falls under this heading, but as we are looking for independence, this variation has not been considered.
- **Crowdsourcing**: In this model, the flow solution (conceptual at least) is obtained by soliciting contributions from a large group of people and especially from the online community. Those involved may or may not be special matter experts, and the output usually at concept level (thought bubbles) as opposed to developed and deeply considered application specific solutions.
- **Co-sourcing**: A more advanced version of Outsourcing characterised by its long-term relationship built on the values of trust, excellent service and quality. While still a third-

party employee, the expert in this model is usually assigned to specific clients which leads to the mutual trust and understanding that differentiates it from the next available resource contracting arrangement. In this partnering posture, there is usually a degree of shared success and responsibility in terms of attaining the flow goal(s).

Using a Multi Criteria Decision Analysis (MCDA) technique, Wellwood [20] found that Co-sourcing strategy, like the ones used for other specialised professional services (finance, tax, legal, IP, IT…), often offers the best overall value for many organisations however every organisation should be considered its own needs however having awareness of the issue and access to special matter experts is best and saves you becoming an expert yourself leaving us (process engineering professionals) to focus on what we were trained for and do best, adding value to materials.

10. Conclusions

Although bulk solids behaviour is complex, the science to describe flow and therefore solve problems, or ideally stop them from occurring in the first place, is well established and readily accessible, and if applied systematically can provide the long-term solutions that avoid (ideally) or address issues of controlled flow of bulk solids in your value-chain.

Three key take away points for the process engineering profession are:

- Bulk science is important, and we should pay attention to it, especially as process engineers whose unit operation selection and optimisation efforts won't be realised without it,
- Despite being the world's largest industrial activity BSH is not covered in undergraduate curriculum. In response you need to be aware of the risks this blind spot poses as well as the best way to get the expertise required for your project(s)/organisations(s) this science needs to be respected and applied to the same degree the science of hydrodynamics is to liquid flows.
- Those who accept this challenge can look forward to a very satisfying and lucrative career with lots of opportunities to advance the science and make a real difference to our world. It is a future-proof specialty area with very few practitioners.

Remember, for many of us there is no business, without flow business!

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