



DESIGN AND MANUFACTURE CASE STUDY

The Use of Systems Engineering Tools in the
Design Development of a BMX Cassette Hub

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Principles of Systems Engineering (ACDA5021)

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Background

Introduction

Freehubs have become the most widely used type of BMX rear hub, as riders have more and more opted for the smaller gearing afforded by the integrated mechanics of these hubs, which, compared to the separate cassette systems, allows for a much smaller drive cog, and are seen as a reliable system. For market driven reasons, pawl-based engagement systems have largely become the standard, due to their low cost and the relatively consumable nature of these parts, which either break or are replaced regularly regardless of how robust they are.

BMX wheels are expected to be able to withstand incredibly rough use, which will all be transferred in some way to the hub. Grind “pegs” are often attached to the axles, which will then be subject to further bending and torsional stresses from peg impacts with hard surfaces, as well as bending stresses transferred through the wheels via the hub. These stresses are mitigated by the additional support afforded by the bicycle frame, to which the hub is mounted, usually by threaded axle, or less often, by bolt-through female axle and slotted dropouts. Often during tricks using the pegs, the hub will also accidentally be subject to direct impacts and abrasions to the side caps and to the body from hard and/or rough surfaces, with the frequency and strength of these accidental impacts dictated by the skill of the rider.

The forces exerted on a rear hub generated solely from pedalling this type of bike are relatively low by comparison to a high end road bike hub or that of a BMX racer, which can see upwards of 100 Nm of force, however on tricks that result in the rider landing backwards and backpedalling, or that otherwise require the locking of the back wheel with pedal pressure, significant levels of torque can be transferred to the engagement mechanism and hub via the driver and chain.

Figure 1 overleaf shows a quick calculation based on conservative values for crank-arm length, driver and chainring and the force generated by an average rider landing from a head-height drop. As can be seen, a bad landing backwards can potentially result in forces of over 35,000 N being exerted on the chain, which would result in even higher forces being spread across the inner driver mechanism and the spoke connection points on the flange, as well as further bending moments along the axle concentrating force around the driver mechanism from the offset axle bearings to either side. This is in addition to any lateral or vertical impacts suffered by the hub in the landing.

These forces will rarely be experienced by a hub alone. BMX chains are rated at up to around 15000 N and it is expected that variations in spoke tension would lead to the structure of the wheel failing before this point. Furthermore for this reason, riders will make every effort to reduce sudden loading of the driver mechanism and wheel in general, through absorbing impacts, attempting to land as straight as possible and measures such as landing backpedalling into heavy backward landings.

BMX Drivetrain Force and Torque Diagram

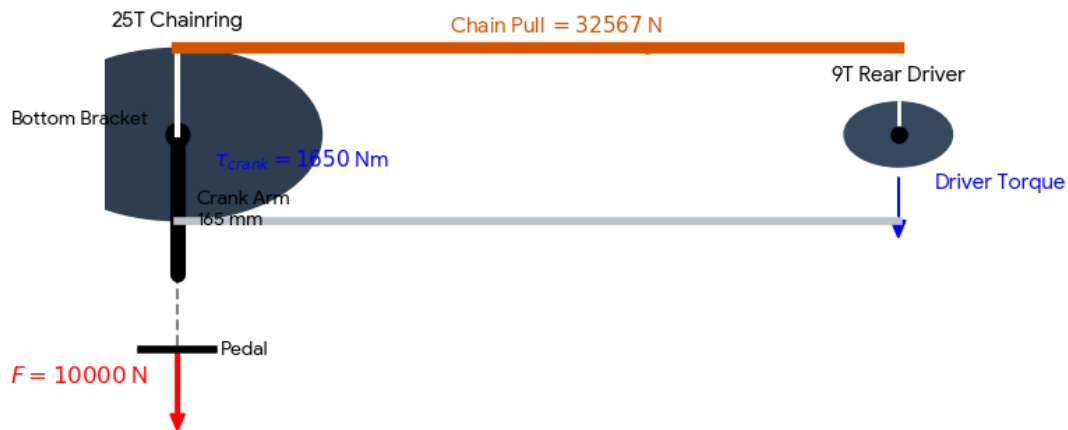


Figure 1: Forces exerted on BMX chain by heavy landing

Due to the relatively small market for BMX parts, and the cost of manufacturing specialist components to the standard required, the majority of hub manufacturers rely on certain standard components produced externally for use in their engagement systems. Components such as the pawl spring(s), bearings, pawls, and the internal-ring gear they engage with, are generally off the shelf components produced by specialist manufacturers.

More recently an increasing number of hub manufacturers have started to incorporate various ratchet-based engagement systems in their hub design, both due to the system's perceived increased robustness and reliability, and as the cost and availability of in-house production for some of the components of these systems has dropped over time to allow a product price-point sufficiently close to that of pawl based systems.



Figure 2: Flybikes "Magneto" Ratchet system hub

Requirements

While cassette hubs are not a new product, their design has been heavily influenced by previous hubs intended for road-bike or mountain bike usage, and due to the relatively small market size for BMX, their manufacture is semi-dependent on use of common components manufactured for other types of hub.

Requirements Gathering

Level 1 requirements were gathered from user focus groups comprising volunteer BMXers, research from BMX forums and other community-run websites, and structured interviews with stakeholders, and were refined through consultation with industry experts and manufacturers.

Summary of discussions

Life-cycle and average use case:

Due to the long running use of these hubs, and the relatively young market for the product, the majority of users had fairly simplistic requirements for their equipment when initially asked, namely that it can takes a beating and continue to work well throughout its life until its rightful destruction (as a result of an over ambitious drop or likewise).

Riders interviewed universally shared the view that a BMX hub should theoretically outlast the average rider, and in the majority of cases this may well be borne out in reality. It is for the outlying 5-10% of riders who consistently push the boundaries of their skill and therefore equipment that these hubs are designed. The majority of users interviewed could count by memory probably every instance of high impacts to their pegs for instance, and such instances were generally few and far between. All agreed however that any peg user could easily subject their bike to around 1000 relatively hard impacts each year, based on an average of 5 hours per week of riding. The number of lateral impacts to wheels was less known, but approximately 60% of those interviewed indicated that their wheel was currently bent as a result of such an impact. All confirmed this had resulted as they would expect in damage to the rim and spokes rather than the hub.

Failures:

due to the relatively tiny market size, strong community, and most likely partly due to rider's proclivity for filming themselves attempting stunts, news of a trend in components failing due to inadequate strength will spread fast and result in likely the almost complete loss of future sales of that particular component, as well as impacting sales of other components. Both groups interviewed mentioned the same historic instances of under-engineered products which had quickly been discovered to suffer a high failure rate when in use, and this information was known by riders too young to have used these components.

Users were realistic regarding the level of use that would realistically be expected to destroy a hub, and did not consider failure through extreme use to reflect negatively on their view of the product. Interestingly, some riders voiced a negative perception of old, "overengineered" products, known to be relatively heavy options. On questioning, most riders preferred a middle ground for weight, although did not believe this should compromise strength.

Pedal slip in normal to hard use, through failure or poor performance of the driver mechanism, was seen as incredibly annoying, and any instance of this would not only put the rider headfirst over the handlebars, but would result in the replacement of the hub in question. Likewise, any jamming of the mechanism would be perceived as a likely fatal fault in the hub.

Engagement mechanism

A small range of pedal free-motion prior to mechanism engagement was considered not only acceptable, but preferable in some cases, due to the margin of error it can provide in reaction times. Overall opinions were mixed on the importance of this, with the majority of users stating that less free-motion is better.

A high percentage of riders interviewed employed pegs on their bike, and all had done so for periods of their riding career.

Functional/Consumer requirements:

Generic Requirements derived from focus groups with users are presented below in Table 1:

Number	Originator	Requirements
1	Customer	Has to be strong
2	Customer	Has to drive the back wheel
3	Customer	Should be able to withstand knocks and scrapes [SIC]
4	Customer	shouldn't move in the dropouts
5	Customer	Should be able to withstand impacts
6	Customer	mechanism needs to be reliable
7	Customer	needs to survive heavy impacts in all directions
8	Customer	no pedal slip and predictable engagement
9	Customer	Needs to be strong enough for pegs
11	Customer	The hub should be relatively lightweight

Table 1: Derived Generic Requirements

Refining Requirements

Translating these into level 2 and level 3 requirements was accomplished through calculation and through further 1 on 1 discussions via social media with a subject matter expert at the BMX Parts manufacturer Odyssey into the average lifecycles and forces experienced by a bmx part. [1]

Figures provided by Odyssey were used as the basis for the performance requirements attached to each functional requirement. Conservative values were also calculated for high level loads that could be experienced by the hub in order to provide a high-end estimate of maximum loading. As the hub however is not directly connected to the driving cranks, any forces transmitted in this manner will propagate through the chain, and as such, the maximum breaking rating of BMX chains (14,800 N) can be applied with a margin to ensure the survival of the hub in this event.

Clamping force was calculated for the standard hardened steel M10*14mm axle with fine teeth, tightened at 40nm of torque (assuming most users will tighten connections at maximum torque with standard hand-tools).

Level 3 Requirements

Level 3 performance requirements for those listed above were derived as per the above process and are presented below in table 2.

Number	Level 3
1	The hub should function effectively for <100,000 cycles of forces at 75% of maximum loading.
2	The driver mechanism must engage with the hub only under loading from the chain.
3	Dropout to flange distance must not be less than 28mm (average tyre width)
4	The axle must secure to the 14mm frame dropouts with a low slip factor and provide at least 15KPa of clamping force on the frame.
5	The axle must be able to withstand shock impacts of 5000 N on the pegs for more than 100,000 cycles.
6	The driver mechanism should operate effectively under maximum elastic deflection of the axle and bearings.
7	The hub must withstand up-to 275 N.m of torque and chain loading of up-to 14,800 N.
8	The driver mechanism should engage within 15° of pedal movement without pedal slip.
9	Axle fixings should provide a 14mm dia mounting surface, and ensure maximum clamping force between 1-12mm washer thickness.

Table 2: Derived Level 3 Performance Requirements

Torque values taken from Google AI.

Pairwise Comparison

The above requirements were refined by the author (as per [2]) and rationalised by entering into a pairwise grid. This rates the relative importance of all requirements in relation to each other, to which interactions between requirements in each column are rated as less, equal or more important in terms of functional effect to the requirements in each row. This is in order to provide a normalised score for the importance of each requirement. This can be seen in Figure 3 overleaf:

		1	2	3	4	5	6	7	8	9	Calc	Calc
	Pairwise comparison of requirements 1 = No Preference, Reciprocal = 1 2 = Slight Preference, Reciprocal = 0.5 5 = Preference, Reciprocal = 0.2 9 = Strong preference = 0.1	The hub should operate effectively after suffering impacts and forces up-to its design loading	The driver mechanism must engage with the hub only under loading from the chain.	Dropout to flange distance must not be less than 28mm (average tyre width)	The axle must secure to the 14mm frame dropouts with a low slip factor and provide at least 15KPa of clamping force on the frame.	The axle must be able to withstand shock impacts of 5000 N on the pegs for more than 100,000 cycles.	The driver mechanism should operate effectively under maximum elastic deflection of the axle and bearings.	The hub must withstand up-to 275 N.m of torque and chain loading of up-to 14,800 N.	The driver mechanism should engage within 15° of pedal movement without pedal slip.	Axle fixings should provide a 14mm dia mounting surface, and ensure maximum clamping force with up-to +11mm washer thickness.	Row Product	nth root of row product
											Total Normalised	
1	The hub should operate effectively after suffering impacts and forces up-to its design loading	1	0.2	9	0.1	2	2	5	9	5	162	2
2	The driver mechanism must engage with the hub only under loading from the chain.	5	1	9	5	9	5	5	9	9	4100625	5
3	Dropout to flange distance must not be less than 28mm (average tyre width)	0.1	0.1	1	0.1	0.2	0.1	2	0.2	0.1	0.0000008	0
4	The axle must secure to the 14mm frame dropouts with a low slip factor and provide at least 15KPa of clamping force on the frame.	9	0.2	1	1	5	2	5	9	5	4050	3
5	The axle must be able to withstand shock impacts of 5000 N on the pegs for more than 100,000 cycles.	0.5	0.1	2	9	1	1	9	1	5	40.5	2
6	The driver mechanism should operate effectively under maximum elastic deflection of the axle and bearings.	0.5	0.2	1	9	9	1	5	9	1	364.5	2
7	The hub must withstand up-to 275 N.m of torque and chain loading of up-to 14,800 N.	0.2	0.2	2	9	9	1	1	1	1	6.48	1
8	The driver mechanism should engage within 15° of pedal movement without pedal slip.	0.1	0.1	1	5	5	9	1	1	1	2.25	1
9	Axle fixings should provide a 14mm dia mounting surface, and ensure maximum clamping force with up to +11mm washer thickness.	0.2	0.1	5	9	9	1	2	1	1	16.2	1
											4105266.93	17.04
												100

Figure 3: Pairwise comparison of Requirements

Here, any relationship where the desired behaviour will be enabled by the fulfilment of each requirement or otherwise depends on its successful implementation, are rated either 1, 3 or 9 while a reciprocal preference to the contrary are rated 0.1, 0.2 and 0.5. This enables a simple multiplication formula for each row that will in effect, score the behaviour negatively or positively to the relevant degree and produce a rating. These results were then normalised to enable a comparison. The results of this exercise were charted and the results are presented in Figure 4 below.

As can be seen, the three requirements with the highest importance in terms of their benefits to other requirements and dependencies on others, are for the hub to be robust, for the engagement mechanism to operate reliably, and to allow for a 14mm minimum diameter axle.

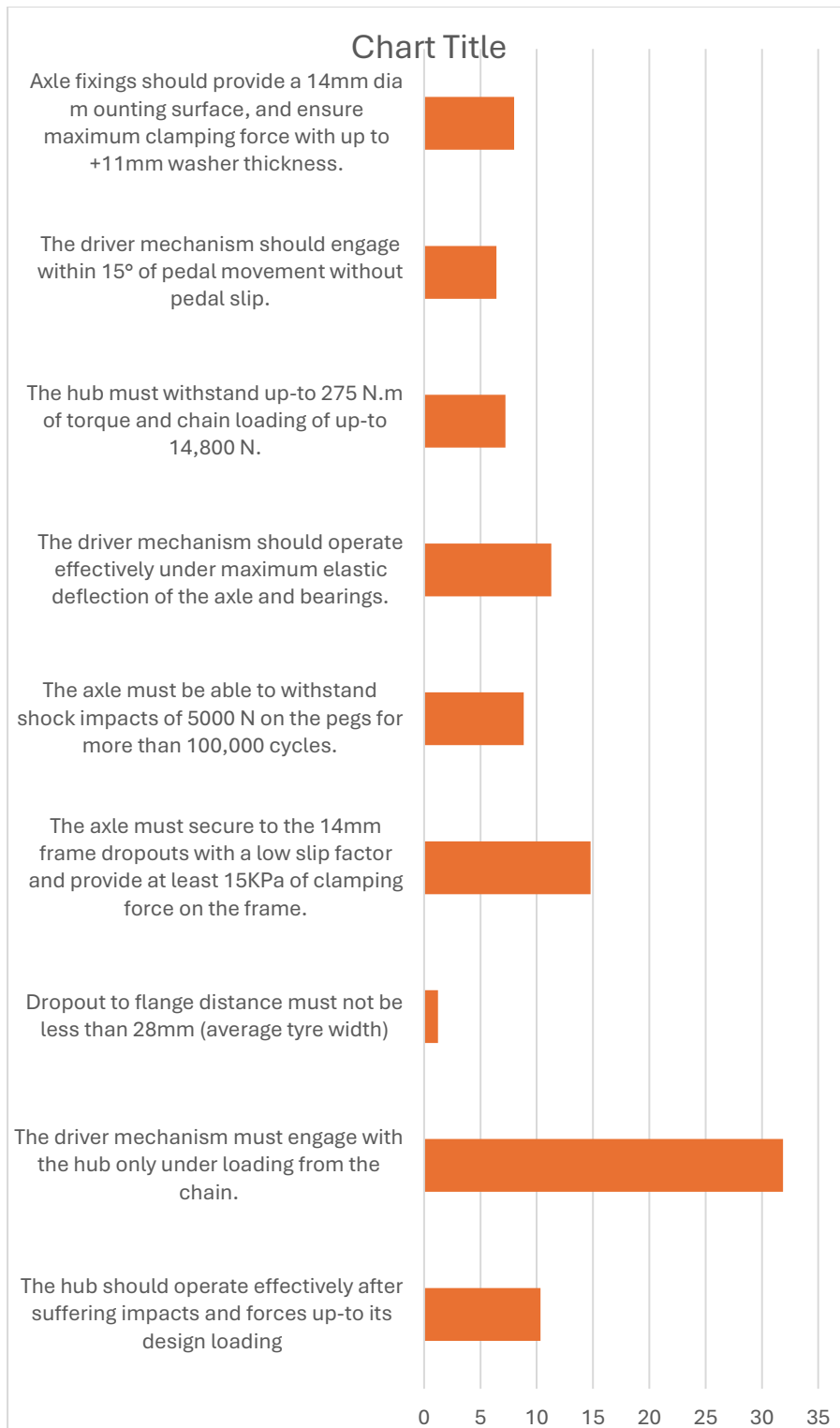


Figure 4: Charted results of Pairwise Comparison

QFD1

Functional Importance Comparison

A use case was generated by the author to reflect the basic life-cycle requirements on a BMX hub, from wheel build to maintenance or removal. A comparison matrix was then populated

from the use case generated and is presented below. This was then used to generate a graph showing the importance for the respective functions. This is shown at figure 6.

[illegible]

Figure 5: QFD1 comparison matrix

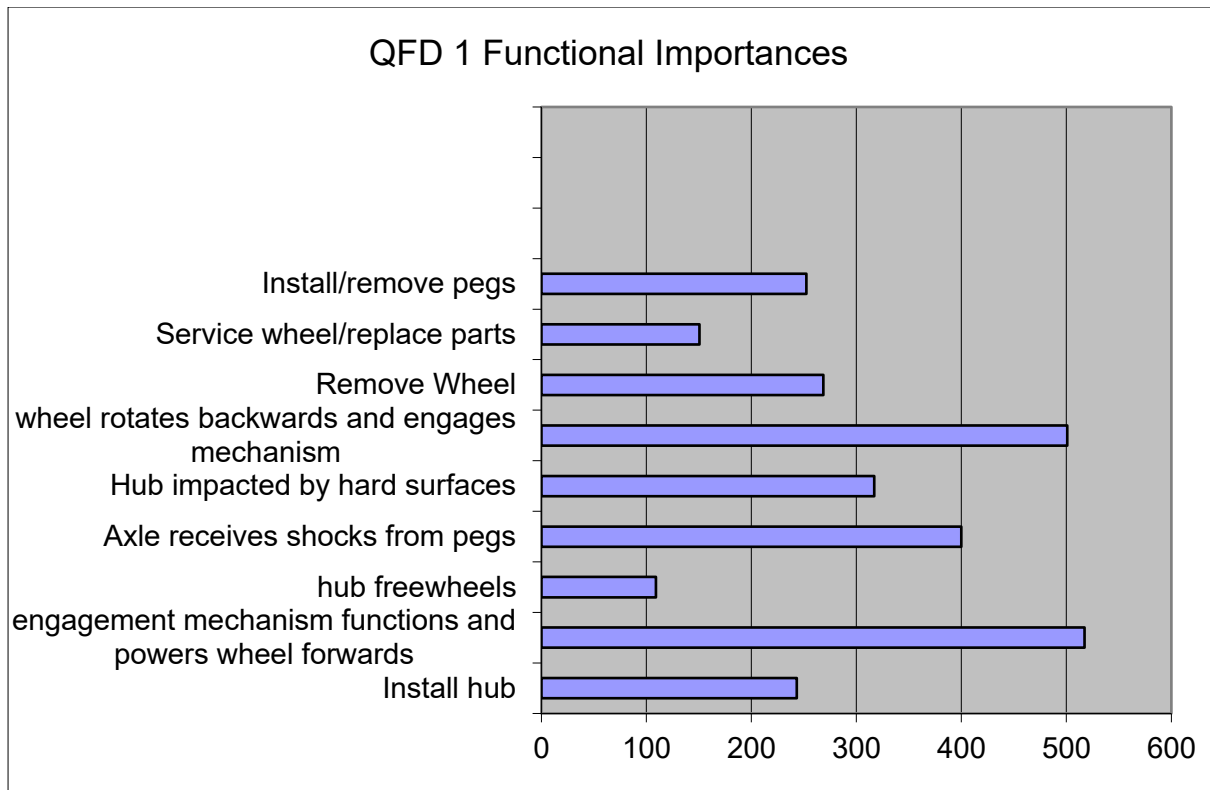


Figure 6: QFD1 Functional Importances

Concept

Architecture

Hub body assembly

Hub body – CNC machined out of aluminium, Comprises flanged largely cylindrical body, with perforations on flanges for spokes, and interface surfaces bearing races and engagement gear

Engagement gear (mechanism for ratchet drive) (hardened steel internal ring gear or star-ratchet, permanently fitted to hub body). [3]

Sealed bearing races – one large Outer diameter (OD), two 14mm internal diameter (ID) races under non-drive flange, and 1 next to the driver as per figure 4.



Figure 7: Cutaway of cassette hub

Driver assembly

Driver body – CNC machined out of Aluminium, comprises the driving cog on one half, with a machined inner surface to seat the axle bearings, with mounting surfaces and recesses for engagement mechanism components, and an O-ring seal with the hub body.

Engagement mechanism - either ratchet star gear or sprung pawls to engage drive teeth on hub body. Pawls usually located in recessed joints machined into driver, and mechanism is either collectively sprung or individually.

Roller bearing race to interface with axle.

Axle Assembly

Axle – hardened steel or titanium axle, threaded on both ends with M14 thread, with bearing stops and mounting surfaces for hub body bearings, and mounting surfaces for driver bearing race.

Drive-side lock-nut – Machined nut to hold driver in place on axle, provides some protection to driver bearings and mating surface for frame dropouts

Non-drive-side cone – screws onto axle on non-drive side to protect bearings from damage and provide mating surface for frame dropouts.

Washers and Nuts to fix axle in place in slotted dropouts.

Alternative engagement mechanisms

Options for alternative driver mechanisms have been employed in the various hubs on the market, with variations in design between all.

Drive ring and Pawl-based mechanisms employ a number of sprung (by mechanical spring or magnet) pawls which engage with unidirectional teeth. The amount of pedal free-motion in this mechanism is determined by the distance any pawl must travel in order to engage with the teeth on the drive ring. This can depend on the number of teeth on the drive ring, and the number of engagement groups among the pawls (i.e. if 2 out of 4 pawls engage together, then there are 2 engagement groups).

Ratchet-style mechanisms are employed in some hubs due to their high number of engagement points (usually equal-to or half of the number of teeth on the drive plate) and correspondingly high strength. These hubs tend towards the higher end of the market in terms of the weight of the mechanism and the cost of the product, but due to their high performance, are often seen as more high end components.

The use of **one-way-locking needle bearing races** may also provide a solution to this requirement. This would provide for a much lighter, and potentially lower cost solution, however there are trade-offs with the load capacity of such a component, and may affect consumer satisfaction for those riders who are used to, or just prefer some free pedal motion prior to the hub engaging.

Function Means Analysis

Using the above concept architecture, a list of components applicable to each function was produced as per figure 5 below. It is worth noting that steel pawl pins are optional and can be replaced with locator seats machined into the hub driver and alternative pawls. This should not affect the analysis as it will be considered under separate controls.

Function	Means													
Build Wheel			hub body	driver body										
Install hub	axle nuts	axle-nut washers	axle	driver body										
engagement mechanism functions and powers wheel forwards	axle nuts	axle-nut washers	driver bearing	driver body	pawl springs	pawls	inner-ring gear	hub body	hub body bearings	axle	locking nut	pawl pins	o-ring	
hub freewheels	axle nuts	axle-nut washers	hub body	hub body bearings	pawl springs	pawls	inner-ring gear	axle	driver body	pawl pins			o-ring	
withstand shocks to axle	axle nuts	axle-nut washers	driver bearing	hub body bearings	hub body	locking nut	locking cone							
withstand impact from hard surfaces	hub body	hub-body bearings	locking nut	locking cone										
wheel rotates backwards and engages mechanism	axle nuts	axle-nut washers	driver bearing	driver body	pawl springs	pawls	inner-ring gear	hub body	hub body bearings	axle	pawl pins	o-ring		
Remove hub	axle nuts	axle-nut washers	axle											
Service Wheel	axle nuts	axle-nut washers	driver bearing	hub body bearings	locking nut	locking cone	hub body	axle	driver body	o-ring				
Install/Remove pegs	axle nuts	axle-nut washers	axle											

Figure 8: Component against function

QFD2

Unsurprisingly, given it's functions, the axle is highlighted as an importance component here, with the axle nuts and washers second. As is apparent, a secure fixing holding the axle to the frame, and a strong axle is highly beneficial to the effective operation of the hub, as is the effective operation of the hub bearings. Figure 7 shows these results charted for comparison.

Figure 9: QFD2 Grid



Noise Factors

A P-Diagram was produced illustrating the various noise factors affecting outputs and analysed with an importance grid, from which the charts in figure 10 and 11 were produced showing the comparative ratings of the various Noise and Control Factors.

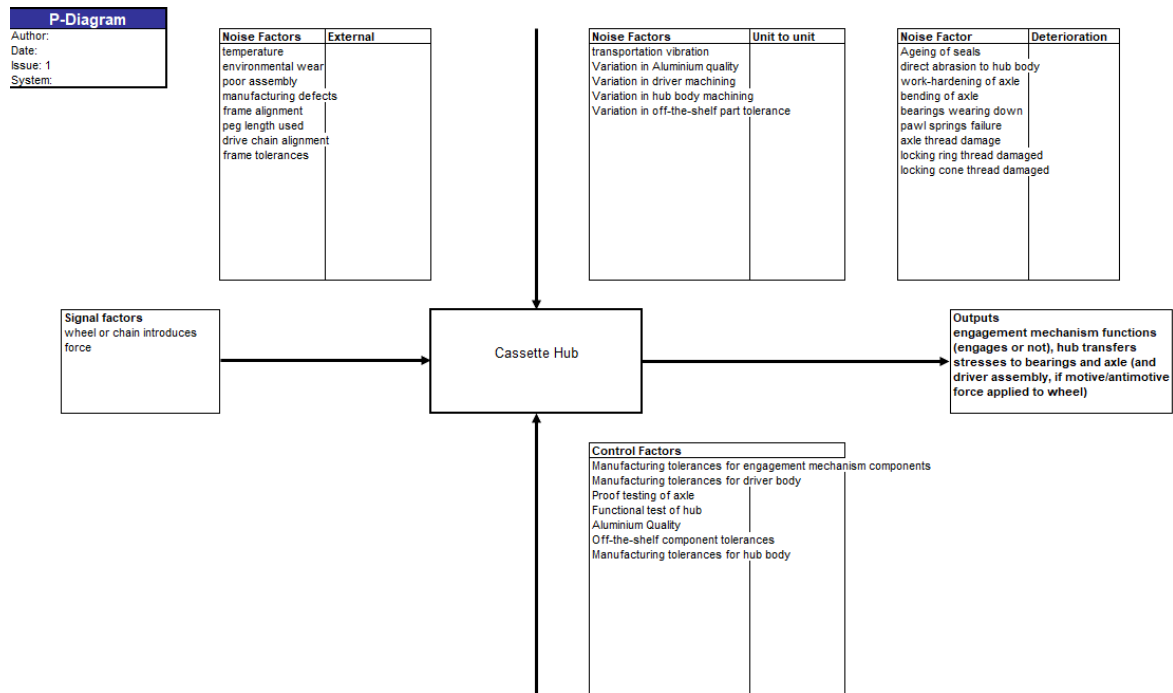


Figure 11: P Diagram of Noise Factors affecting outputs

Performance Characteristics	Weighting of design parameter	NOISE FACTORS																							Relative Importance of noise in meeting performance via control factor	
		Unit to Unit Variation					Deterioration										External									
		Wip	Wip	Wip	Wip	Wip	Raw Mat'	Raw Mat'	Raw Mat'	Raw Mat'	Raw Mat'	Raw Mat'	Raw Mat'	Raw Mat'	Environment	Environment	Human	Environment	Environment	Environment	Environment	Environment	Total			
		Transportation vibration	variation in Aluminium quality	variation in driver machining	variation in hub body machining	variation in off-the-shelf part tolerance	Ageing of seals	direct abrasion to hub body	work-hardening of axle	bending of axle	bearings wearing down	pawl springs failure	axle thread damage	locking ring thread damage	locking cone thread damage	temperature	environmental wear	poor assembly	manufacturing defects	frame alignment	peg length used	drive chain alignment	frame tolerances			
Design control parameters																										
Manufacturing tolerances for engagement mechanism components	9		1	3	3	3				3	3	3	1	1				3	3	3		3		63	567	
Manufacturing tolerances for driver body	9		1	3	3	3	1			3	3					1		3	3					39	351	
Proof testing of axle	9			3		3		3	3	3						1			3		3			52	468	
Functional test of hub	9		3	3	3	3							3	3	3		3	3	3					69	621	
Aluminium Quality	9		3	3	3			3											1					46	414	
Off-the-shelf component tolerances	9				3	3			3	3	3	3						3						48	432	
Manufacturing tolerances for hub body	9		3		3	3												3	3					39	351	
Relative importance of noise factor:			0	261	486	405	432	9	189	108	270	81	162	90	117	27	18	54	189	198	0	81	27	0		
Team:																										
Date completed:																										
			100																							

Figure 12: Noise Factors analysis

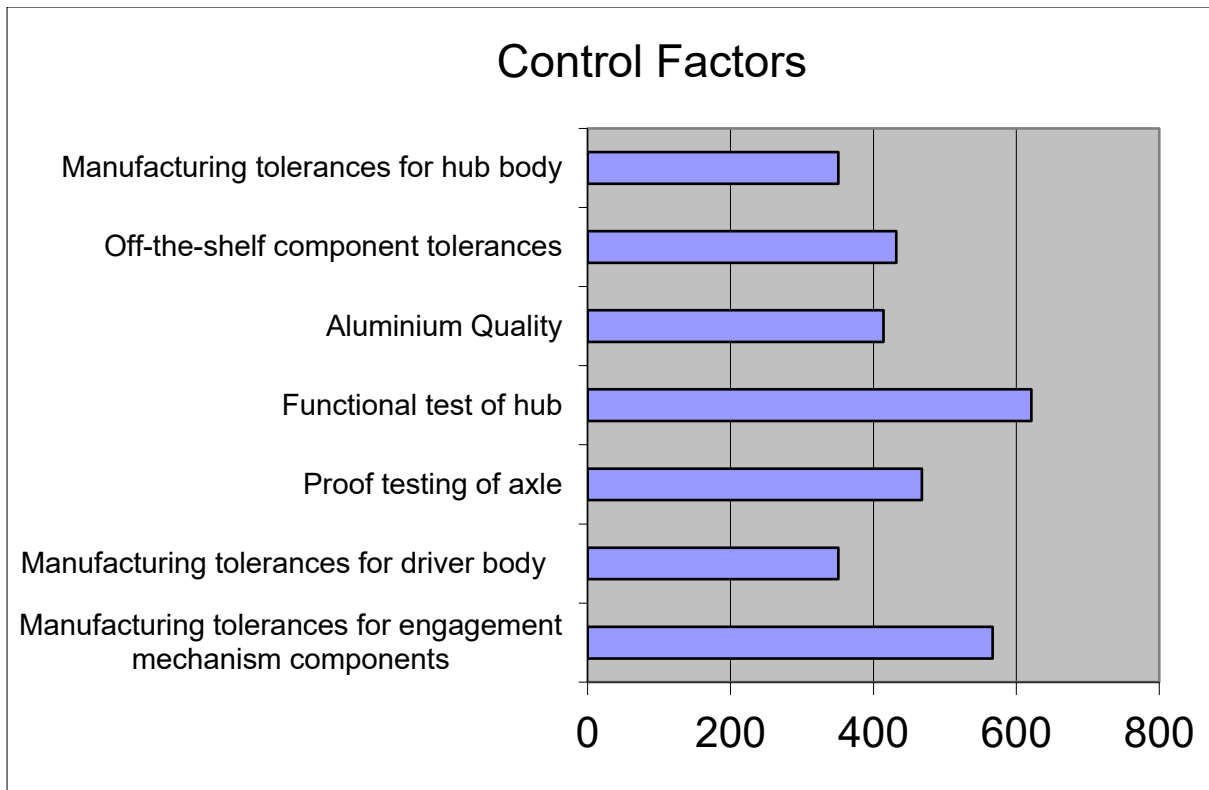


Figure 13: Control Factors Importance

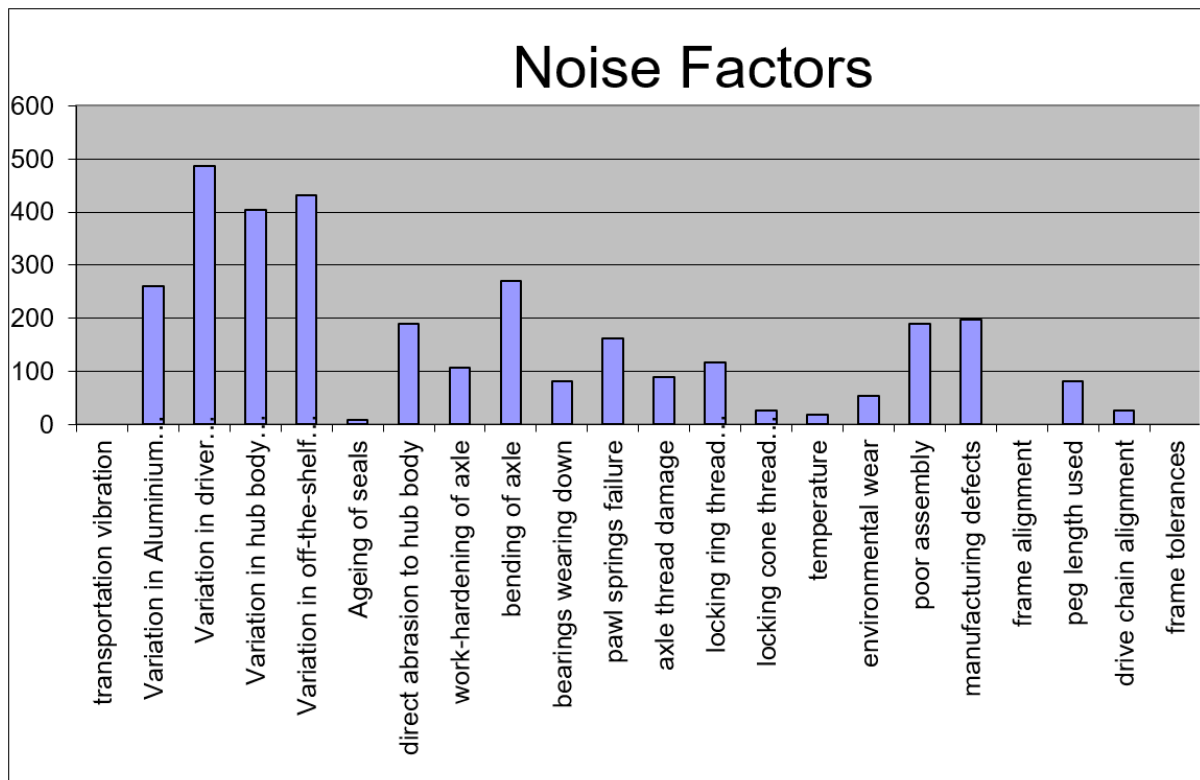


Figure 14: Noise Factors Importance

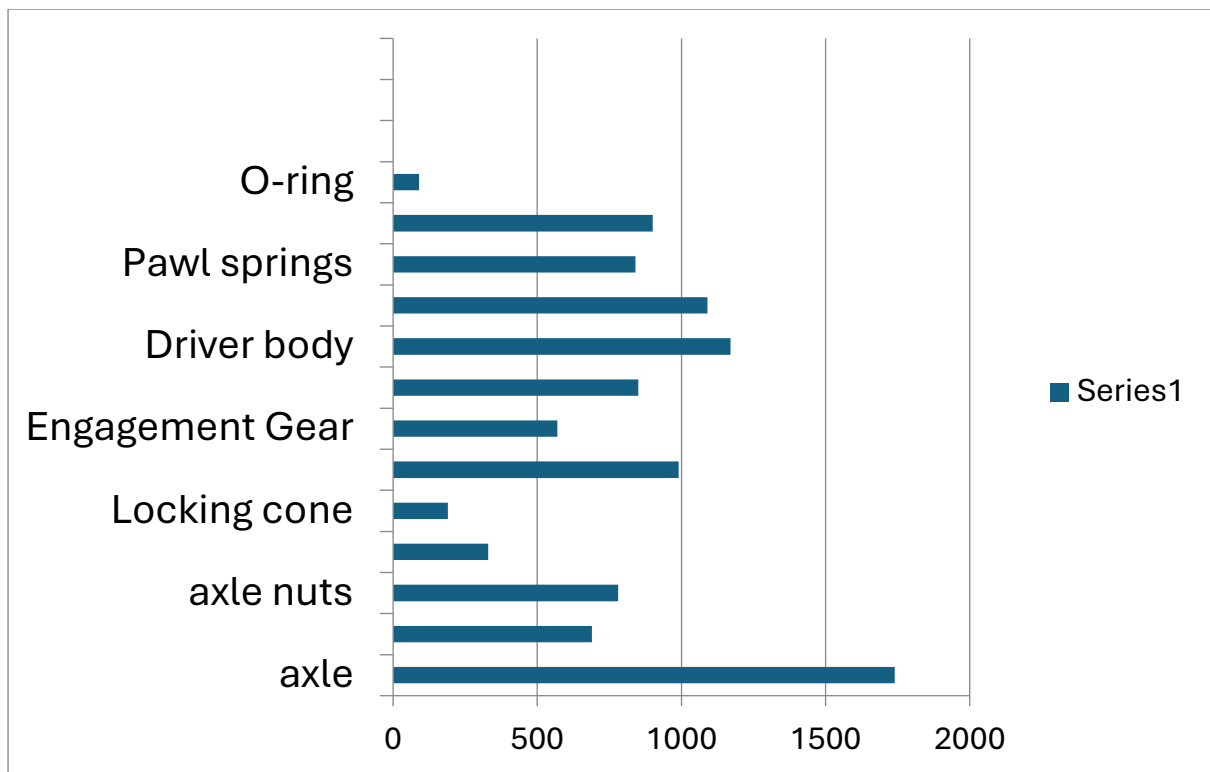
Component Functionality

The Concept Architecture was broken down into its individual components and listed here in the below table alongside the functions they fill.

Component	Functionality
axle	Provides means of attachment to BMX Frame
	Provides mounting surface for driver bearings
	Provides mounting surface for hub body bearings
	Provides mounting surface for pegs
	transmits shocks from wheel into bmx frame
axle washers	distribute shock and force across axle nut
axle nuts	tighten against frame and axle thread to secure axle to BMX frame
locking nut	tighten against roller bearing inner race and axle thread to hold driver
	Interface with frame to ensure good mating surface
Locking cone	Tighten against hub bearings inner race to provide environmental protection
	Interface with frame to ensure good mating surface
Hub body	Provide mounting holes for wheel spokes
	Provide mounting surfaces for bearings
	holds engagement mechanism in place
	rotates around axle when wheel in motion
Engagement Gear	Provide engagement surface for pawls
	Transmit force between driver and hub body
Hub bearings	rotate around axle while wheel is in motion
	transmits forces from hub body into axle
Driver body	Engages with drive chain
	Rotates around axle when chain in motion
	provides mounting recesses for pawls
	provides mounting surface for bearings
	provides mounting recesses for pawl springs
	provides mounting recesses for pawls
	provides mounting recess for o-ring
	creates seal with hub body
driver roller bearing	Rotates around axle
	transmit forces from driver to axle
Pawl springs	push pawls into engagement gear
pawls	engage with gear on hub body
	transmit forces between driver and hub
	rotate around pivot point

The above functions were then transcribed into a further QFD2 Importance analysis to determine which components were most vital as per figure 12 below:

In future iterations of this form of analysis, components can be subjected to the same process as above to highlight critical factors in their manufacture that may influence desired outputs. This is used to reveal emergent behaviour and dependencies between components and can direct a designer to the most design-critical components and highlight the need for strict manufacturing tolerances, quality control etc in their manufacture.



References

- [1] R. Garry, "Social media discussion with Jim Bauer (Odyssey BMX) on life-cycles and testing of BMX components," Bristol, 2026.
- [2] D. S. Burge, "A Functional Approach to Quality Function Deployment," Systems Engineering, 2007.
- [3] C. BMX, "chimerabmx.com," Chimera BMX, July 2015. [Online]. Available: <https://chimerabmx.com/blogs/archive/all-about-hub-engagement?srsltid=AfmBOoornFScXRpB4iwfOtJb3Tki8yq5ANbgbu31zeXnUtt9lkH-mXDF>. [Accessed August 2026].